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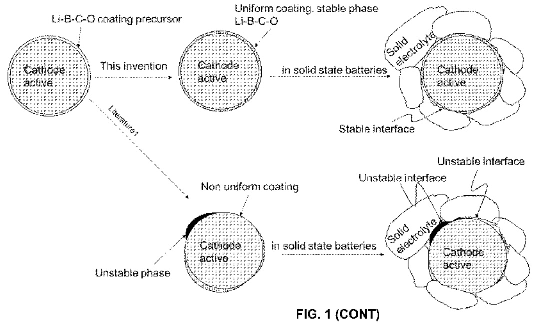

FIG. 1 (CONT)

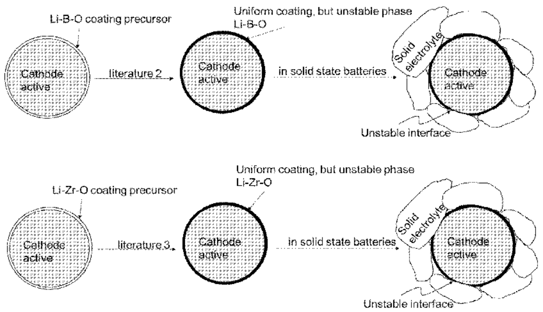

FIG. 1

(57) Abstract: Provided herein are new processes for coating a cathode active material with a solution that includes lithium and optionally boron. Also provided herein are new cathode active materials having a coating which includes lithium carbonate and lithium borate. Also provided herein are new cathode active materials having one or two coating thereupon which increase the stability of the cathode active material at high voltage. In some examples, one of the coatings is $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$; $Li_xZr_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$; or $Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$.

[Continued on next page]

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Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

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CATHODE COATING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The application claims priority to, and the benefit of, U.S. Provisional Patent Application Nos. 63/075,800, filed September 8, 2020, and titled CATHODE COATING; 63/161,388, filed March 15, 2021, and titled CATHODE COATING; 63/170,321, filed April 2, 2021, and titled CATHODE COATING; and 63/173,184, filed April 9, 2021, and titled CATHODE COATING, the entire contents of each patent application are herein incorporated by reference in their entirety for all purposes.

FIELD

[0002] The present disclosure concerns chemical coatings for cathode active materials, which are useful in cathodes (*i.e.*, positive electrodes) of rechargeable lithium-batteries for reversibly storing lithium ions (Li^+).

BACKGROUND

[0003] There is currently an unmet need in the rechargeable lithium battery field directed to cathode active materials which are stable at high voltage (*e.g.*, 4.2 V versus lithium metal) and/or high temperature (e.g., 60 °C). The instability tends to result in increases in internal resistance in the battery, when the battery is stored or when the battery is used, or both.

[0004] Solid electrolyte materials tend not to be stable at high voltage or high temperature. Solid electrolyte materials may react with cathode active materials. Cathode active materials may also oxidize when exposed to high voltage or high temperature. These are a few of the reasons for battery performance degradation. Some researchers have tried to coat cathode active materials with $LiNbO_3$, Li_2ZrO_3, and $LiTaO_3$ to prevent this oxidative. *See* for example, US 2016/0156021 A1; US 2019/0044146 A1; and US 9,692,041 B2. *See* also Chem. Mater. 2018, 30, 22, 8190–8200, (doi.org/10.1021/acs.chemmater.8b03321); *Adv. Energy Mater.* 2020, 1903778 (doi.org/10.1002/aenm.201903778); and *Journal of Power Sources* Volume 248, 15 February 2014, Pages 943-950, (doi.org/10.1016/j.jpowsour.2013.10.005). However, these previously reported coatings had poor stability and/or suffered from other disadvantages. For example, at potentials as high as 4.2V (vs Li/Li^+), the internal resistance of these coatings increased rapidly when in a charged state. For these and other reasons, these previously reported coatings were inferior in several regards.

[0005] Set forth herein are solutions to this and other problems in the relevant field.

SUMMARY

[0006] Set forth herein is a composition comprising: a cathode active material; and a coating in contact with the cathode active material, wherein: the coating comprises a member selected from lithium, oxygen, zirconium, phosphorus, or a combination thereof; the coating is amorphous based on x-ray diffraction pattern analysis; the coating comprises crystalline domains based on transmission electron microscopy (TEM) analysis.

[0007] Set forth herein is a coated cathode active material, comprising: a cathode active material and a coating in contact with the cathode active material, wherein the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, and 31.7 ° (± 0.5 °) (2Θ), when measured using Cu (Kα) radiation at 25 °C; and wherein the peak intensity ratio (k) of the peak at 30.3 ° degree (2Θ) relative to the peak at 31.7 ° degree (2Θ) is greater than 1 or less than 2.

[0008] Set forth herein is a coated cathode active material, comprising: a cathode active material; wherein the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises Li_3BO_3, $Li_3B_{11}O_{18}$, $Li_xB_yO_z$, or a combination thereof; and wherein the first coating contacts the cathode active material; and the second coating contacts the first coating. In the formula, $Li_xB_yO_z$, x is from greater than, or equal to, 0.2, to less than, or equal to, 0.75; y is from greater than, or equal to, 0.5, to less than, or equal to 1.6; and z is from greater than, or equal, to 1.5 to less than, or equal to 2.6. This is equivalently written as $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$.

[0009] Also set forth herein is a process for making a coated cathode active material, comprising the following steps: coating a cathode active material with a solution of LiOH; removing the solvent from the solution coating the cathode active material to provide a first material; heating the first material under dry air conditions to form a heated first material; coating the heated first material with a solution of LiOH and a boron source to form a second material; and heating the second material to form a coated cathode active material.

[0010] Also set forth herein is a process for making a coated cathode active material, comprising the following steps: coating a cathode active material with a solution of LiOH and a boron source; removing the solvent from the solution coating the cathode active material to provide a coated cathode active material; and heating the coated cathode active material under dry air conditions to form a coated cathode active material.

[0011] Also set forth herein is a coated cathode active material, comprising: a cathode active material and a coating in contact with the cathode active material, wherein the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 26.2 ° and 27.4 ° (± 0.5 °) (2Θ), when measured using Cu (Kα) radiation at 25 °C.

BRIEF DESCRIPTIONS OF THE DRAWINGS

[0012] FIG. 1 is a schematic illustrating certain differences between certain aspects of the instant disclosure and previously published documents.

[0013] FIG. 2 is an x-ray powder diffraction pattern of Examples A, B, C, D, and Comparative Example E.

[0014] FIG. 3 are test results from the stability tests in Example 14.

[0015] FIG. 4 is a plot summarizing the change in area-specific resistance (ΔR) for the battery cells tested in Examples 14 and 15.

[0016] FIG. 5 shows a scanning electron microscopy image from Example 3.

[0017] FIG. 6 shows an x-ray diffraction (XRD) pattern for the crystalline LZO coating prepared in Example 11.

[0018] FIG. 7 shows an x-ray diffraction pattern for the amorphous LZO coating prepared in Example 15.

[0019] FIG. 8 shows transmission electron microscopy (TEM) image for the LZO-coated active material in Example 15.

DETAILED DESCRIPTION

[0020] Set forth herein are coatings for cathode active materials. In some examples, the cathode active material has one coating. In other examples, the cathode active material has two coatings. In certain examples, the cathode active material with one coating has a crystalline coating, as determined by XRD. In yet other examples, the cathode active material with one coating has an amorphous coating, as determined by XRD. In some examples, a coating on the cathode active material contains lithium, boron, oxygen, or a combination thereof. In some other examples, a coating on the cathode active material contains lithium boron, carbon, oxygen, or a combination thereof. In some other examples, a coating on the cathode active material contains lithium, oxygen, zirconium, phosphorus, or a combination thereof. Certain of these coatings may prevent, or delay, the aforementioned oxidation reactions which were noted as a reason for battery performance degradation. When used in batteries, the newly disclosed coated cathode active materials set forth herein result in more stable batteries.

DEFINITIONS

[0021] As used herein, the term "about," when qualifying a number, *e.g.*, about 15 % w/w, refers to the number qualified and optionally the numbers included in a range about that qualified number that includes ± 10% of the number. For example, about 15 % w/w includes 15 % w/w as well as 13.5 % w/w, 14 % w/w, 14.5 % w/w, 15.5 % w/w, 16 % w/w, or 16.5 % w/w. For example, "about 75 °C," includes 75 °C as well 68 °C, 69 °C, 70 °C, 71 °C, 72 °C, 73 °C,
74 °C, 75 °C, 76 °C, 77 °C, 78 °C, 79 °C, 80 °C, 81 °C, 82 °C, or 83 °C.

[0022] As used herein, "selected from the group consisting of" refers to a single member from the group, more than one member from the group, or a combination of members from the group. A member selected from the group consisting of A, B, and C includes, for example, A only, B only, or C only, as well as A and B, A and C, B and C, as well as A, B, and C.

[0023] As used herein the phrase "dry air," refers to air with a reduced amount of humidity. Dry air may be supplied in a clean room. Dry air is characterized as having a dew point less than -70°C.

[0024] As used herein the phrase "cathode active material," refers to a material which can intercalate lithium ions or react with lithium ions in a reversible manner. Examples include $LiMPO_4$ (M=Fe, Ni, Co, Mn); $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24; $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2; a nickel cobalt aluminum oxide; $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0 \leq x \leq 1$, $0 \leq y \leq 1$, and $0 \leq z \leq 1$; and $LiNi_xCo_yAl_zO_2$, wherein

$x+y+z=1$, and $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$. In these formula, x, y, and z are chosen so that the formula is charge neutral.

[0025] As used herein the phrase "characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at," means that when the material is analyzed using x-ray powder diffraction, according to the techniques in the Examples, the sample will be observed to have at least the recited XRD peaks and possibly other peaks. Peaks are places of high intensity in the XRD pattern which are indicative of d-spacing (lattice spacing) of the crystalline unit cell which is inducing the observed XRD pattern when x-rays are incident upon the material being analyzed by XRD.

[0026] As used herein the phrase "the peak intensity ratio (k) of the peak at 30.3 degree (2Θ) relative to the peak at 31.7 degree (2Θ) is greater than 1 or less than 2," refers to the ratio of XRD peak intensity (I) at 30.3 degree (2Θ) relative to the peak intensity at 31.7 degree (2Θ): $k= I\,(30.3) / I\,(31.7)$.

[0027] As used herein the phrase "solid-state cathode refers to a cathode which does not include any liquid-phase electrolytes. As used herein, the terms "cathode" and "anode" refer to the electrodes of a battery. The cathode and anode are often referred to in the relevant field as the positive electrode and negative electrode, respectively. During a charge cycle in a Li-secondary battery, Li ions leave the cathode and move through an electrolyte, to the anode. During a charge cycle, electrons leave the cathode and move through an external circuit to the anode. During a discharge cycle in a Li-secondary battery, Li ions migrate towards the cathode through an electrolyte and from the anode. During a discharge cycle, electrons leave the anode and move through an external circuit to the cathode. As used herein, the phrase "positive electrode" refers to the electrode in a secondary battery towards which positive ions, *e.g.*, Li^+, conduct, flow or move during discharge of the battery. As used herein, the phrase "negative electrode" refers to the electrode in a secondary battery from where positive ions, *e.g.*, Li^+, flow or move during discharge of the battery. In a battery comprised of a Li-metal electrode and a conversion chemistry, intercalation chemistry, or combination conversion/intercalation chemistry-including electrode (*i.e.*, cathode active material; *e.g.*, NiF_x, NCA, $LiNi_xMn_yCo_zO_2$ [NMC] or $LiNi_xAl_yCo_zO_2$ [NCA], wherein $x+y+z=1$), the electrode having the conversion chemistry, intercalation chemistry, or combination conversion/intercalation chemistry material is referred to as the positive electrode. In some usages, cathode is used in place of positive electrode, and anode is used in place of negative electrode. When a Li-secondary battery is charged, Li ions move from the positive electrode (*e.g.*, NiF_x, NMC, NCA) towards the negative electrode (*e.g.*, Li-metal). When a Li-secondary battery is discharged, Li ions move towards the positive electrode and from the negative electrode.

[0028] As used herein the phrase "solid separator" refers to a Li^+ ion-conducting material that is substantially insulating to electrons (*e.g.*, the lithium ion conductivity is at least 10^3 times, and often 10^6 times, greater than the electron conductivity), and which acts as a physical barrier or spacer between the positive and negative electrodes in an electrochemical cell.

[0029] As used herein, the term "LPSI" refers to a lithium conducting electrolyte comprising Li, P, S, and I. More generally, it is understood to include $aLi_2S+bP_2S_y+cLiX$ where X=Cl, Br, and/or I and where y=3-5 and where a/b=2.5-4.5 and where (a+b)/c=0.5-15.

[0030] As used herein, "LSTPS" refers to a material characterized by the formula $Li_aMP_bS_c$, where M is Si, Ge, Sn, and/or Al, and where $2 \leq a \leq 8$, $0.5 \leq b \leq 2.5$, $4 \leq c \leq 12$. "LSPS" refers to an electrolyte material characterized by the formula $L_aSiP_bS_c$, where $2 \leq a \leq 8$, $0.5 \leq b \leq 2.5$, $4 \leq c \leq 12$. LSPS refers to an electrolyte material characterized by the formula $L_aSiP_bS_c$, wherein, where $2\leq a\leq 8$, $0.5\leq b\leq 2.5$, $4 \leq c\leq 12$, $d<3$. Exemplary LSTPS materials are found, for example, in International Patent Application No. PCT/US14/38283, SOLID STATE CATHOLYTE OR ELECTROLYTE FOR BATTERY USING $Li_AMP_BS_C$ (M = SI, GE, AND/OR SN), filed May 15, 2014, and published as WO 2014/186634, on November 20, 2014, which is incorporated by reference herein in its entirety. Exemplary LSTPS materials are found, for example, in US Patent Application No. 14/618,979, filed February 10, 2015, and published as Patent Application Publication No. 2015/0171465, on June 18, 2015, which is incorporated by reference herein in its entirety. When M is Sn and Si -- both are present. As used herein, "LSTPSO" refers to LSTPS that is doped with, or has, O present. In some examples, "LSTPSO" is a LSTPS material with an oxygen content between 0.01 and 10 atomic %. "LSPS" refers to an electrolyte material having Li, Si, P, and S chemical constituents. As used herein "LSTPS" refers to an electrolyte material having Li, Si, P, Sn, and S chemical constituents. As used herein, "LSPSO" refers to LSPS that is doped with, or has, O present. In some examples, "LSPSO" is a LSPS material with an oxygen content between 0.01 and 10 atomic %. As used herein, "LATP," refers to an electrolyte material having Li, As, Sn, and P chemical constituents. As used herein "LAGP" refers to an electrolyte material having Li, As, Ge, and P chemical constituents. As used herein, "LSTPSO" refers to a catholyte material characterized by the formula $Li_aMP_bS_cO_d$, where M is Si, Ge, Sn, and/or Al, and where $2 \leq a \leq 8$, $0.5 \leq b \leq 2.5$, $4 \leq c \leq 12$, $d < 3$. LSTPSO refers to LSTPS, as defined above, and having oxygen doping at from 0.1 to about 10 atomic %. LPSO refers to LPS, as defined above, and having oxygen doping at from 0.1 to about 10 atomic %.

[0031] As used herein, "LTS" refers to a lithium tin sulfide compound which can be described as Li_2S-SnS_2, Li_2S-SnS, Li-S-Sn, and/or a catholyte consisting essentially of Li, S, and Sn. The composition may be $Li_xSn_yS_z$ where $0.25 \leq x \leq 0.65$, $0.05 \leq y \leq 0.2$, and $0.25 \leq z \leq 0.65$. In some examples, LTS is a mixture of Li_2S and SnS_2 in the ratio of 80:20, 75:25, 70:30, 2:1, or 1:1 molar ratio. LTS may include up to 10 atomic % oxygen. LTS may be doped with Bi, Sb, As, P, B, Al, Ge, Ga, and/or In. As used herein, "LATS" refers to LTS, as used above, and further comprising Arsenic (As).

[0032] As used herein the phrase "annealing," refers heating a material, *e.g.*, from 100° C. to 400° C, or *e.g.*, 100°C, 150°C, 200°C, 250°C, 300°C, or 350°C in a controlled atmosphere, *e.g.*, dry air.

[0033] As used herein the phrase "stable at high voltage," refers to a material (*e.g.*, a coated cathode active material) which does not react at high voltage (4.2 V or higher versus Li metal) in a way that materially or significantly degrades the ionic conductivity or resistance of the material when held at high voltage for at least three days. Herein, a material or significant degradation in ionic conductivity or resistance is a reduction in ionic conductivity, or an increase in resistance, by an order of magnitude or more. As used herein, the term "high voltage" means at least 4.2V versus lithium metal (*i.e.*, v. Li). High voltage may also refer to higher voltage, e.g., 4.3, 4.4, 4.5, 4.6, 4.7, 4.8. 4.9, 5.0 V or higher.

[0034] As used herein, high voltage means 4.2 V or larger versus a lithium metal reference electrode (which is at 0V) unless specified to the contrary.

[0035] As used herein the phrase "stable at high temperature," refers to a material (*e.g.*, a coated cathode active material) which does not react at high temperature (60 °C or higher) in a way that materially or significantly degrades the ionic conductivity or resistance of the material when held at high temperature for at least three days.

[0036] As used herein, area-specific resistance (ASR) is measured by electrochemical cycling using an Arbin or Biologic instrument unless otherwise specified to the contrary.

[0037] As used herein, ionic conductivity is measured by electrical impedance spectroscopy methods known in the art.

[0038] Herein, the term “Li-B-C-O,” refers to a material, which may have the empirical formula $Li_{(3-x)}B_{(1-x)}C_xO_3$, wherein $0<x<0.65$, and that is isostructural with crystalline Li_2CO_3. In some examples, the XRD pattern for Li-B-C-O indicates the formation of a solid solution with a minor phase distributed in a major phase.

[0039] As used herein, the term “LZO” refers to Li_2ZrO_3, ZrO_2, or a combination thereof. LZO may be crystalline, amorphous, or a combination thereof. For example, LZO may include crystalline ZrO_2 and amorphous Li_2ZrO_3. For example, LZO may include ZrO_2. For example, LZO may include Li_2ZrO_3.

COMPOSITIONS OF MATTER

[0040] In certain examples, set forth herein is a composition comprising: a cathode active material; and a coating in contact with the cathode active material, wherein: the coating comprises a member selected from lithium, oxygen, zirconium, phosphorus, or a combination thereof; wherein the coating comprises crystalline domains based on transmission electron microscopy (TEM) analysis.

[0041] In some of these examples, set forth herein is a composition comprising: a cathode active material; and a coating in contact with the cathode active material, wherein: the coating comprises a member selected from lithium, oxygen, zirconium, phosphorus, or a combination thereof; the coating is amorphous based on x-ray diffraction pattern analysis; the coating comprises crystalline domains based on transmission electron microscopy (TEM) analysis. An example is shown in FIG. 8. In FIG. 8, the coating on the NMC active material has crystalline order as determined by TEM. This crystalline order is adjacent to the NMC active material. FIG. 8 also shows an amorphous component to this coating. Both the crystalline and amorphous components are labeled in FIG. 8. The amorphous component surrounds the crystalline component. As evidenced by FIG. 7, when the coating is analyzed by XRD, the coating appears amorphous on account of the lack of well-defined, high-intensity XRD peaks.

[0042] In some examples, including any of the foregoing, the coating has the chemical formula:

$Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$;

$Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$; or

$Li_xC_yO_z$, wherein $0.4 \leq x \leq 1.8$, $0.1 \leq y \leq 1$, and $1 \leq z \leq 1.8$.

[0043] In certain examples, the coating is $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$.

[0044] In certain other examples, the coating is $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$.

[0045] In yet other examples, the coating is $Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$.

[0046] In yet other examples, the coating is $Li_xC_yO_z$, wherein $0.4 \leq x \leq 1.8$, $0.1 \leq y \leq 1$, and $1 \leq z \leq 1.8$.

[0047] In some examples, including any of the foregoing, the coating further comprises amorphous domains based on TEM analysis in addition to the crystalline domains based on transmission electron microscopy analysis.

[0048] In some examples, including any of the foregoing, the crystalline domains are in contact with the cathode active material.

[0049] In some examples, including any of the foregoing, the amorphous domains are not in contact with the cathode active material.

[0050] In some examples, including any of the foregoing, the coating has a thickness, T, as determined by TEM analysis, that is $1 \text{ nm} \leq T \leq 20 \text{ nm}$.

[0051] In some examples, including any of the foregoing, T is about 1, about 5 nm, or about 10 nm. In some examples, including any of the foregoing, T is 1 nm. In some examples, including any of the foregoing, T is 2 nm. In some examples, including any of the foregoing, T is 3 nm. In some examples, including any of the foregoing, T is 4 nm. In some examples, including any of the foregoing, T is 5 nm. In some examples, including any of the foregoing, T is 6 nm. In some examples, including any of the foregoing, T is 7 nm. In some examples, including any of the foregoing, T is 8 nm. In some examples, including any of the foregoing, T is 9 nm. In some examples, including any of the foregoing, T is 10 nm.

[0052] In some examples, including any of the foregoing, the coating crystalline domains do not lattice match the crystalline domains of the cathode active material, as determined by TEM analysis.

[0053] In some examples, including any of the foregoing, the composition further comprises a second coating in contact with the coating.

[0054] In some examples, including any of the foregoing, the second coating has a chemical formula which is not the same as the chemical formula of the coating.

[0055] In some examples, including any of the foregoing, the second coating has the chemical formula:

$Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$; or

$Li_xIn_yCl_z$, wherein $2 \leq x \leq 4$, $0 \leq y \leq 2$, and $5 \leq z \leq 7$.

[0056] In some examples, including any of the foregoing, the second coating is amorphous as determined by TEM analysis.

[0057] In some examples, including any of the foregoing, the second coating is crystalline as determined by TEM analysis.

[0058] In some examples, including any of the foregoing, the second coating is Li_3BO_3.

[0059] In some examples, including any of the foregoing, the coating is Li_3InCl_6.

[0060] In some examples, including any of the foregoing, the first coating is $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$.

[0061] In some examples, including any of the foregoing, the first coating is a lithium zirconium oxide.

[0062] In some examples, including any of the foregoing, the first coating is a Li_2ZrO_3.

[0063] In some examples, including any of the foregoing, the first coating is $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$.

[0064] In some examples, including any of the foregoing, the first coating is $Li_3(PO_4)$.

[0065] In some examples, including any of the foregoing, the first coating is $Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$.

[0066] In some examples, including any of the foregoing, the first coating is $LiZr_2(PO_4)_3$

[0067] In some examples, including any of the foregoing, the coating or the second coating, or both, further comprises a member selected from the group consisting of Li_2CO_3, Li_3BO_3, $Li_3B_{11}O_{18}$, Li_2ZrO_3, Li_3PO_4, Li_2SO_4, $LiNbO_3$, $Li_4Ti_5O_{12}$, $LiTi_2(PO_4)_3$, $LiZr_2(PO_4)_3$, LiOH, LiF, Li_4ZrF_8, $Li_3Zr_4F_{19}$, Li_3TiF_6, $LiAlF_4$, $LiYF_4$, $LiNbF_6$, ZrO_2, Al_2O_3, TiO_2, ZrF_4, AlF_3, TiF_4, YF_3, NbF_5, and combinations thereof.

[0068] In some examples, including any of the foregoing, the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn); $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24; $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2; a nickel cobalt aluminum oxide; $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0 \leq x \leq 1$, $0 \leq y \leq 1$, and $0 \leq z \leq 1$; and $LiNi_xCo_yAl_zO_2$, wherein $x+y+z=1$, and $0 \leq x \leq 1$, $0 \leq y \leq 1$, and $0 \leq z \leq 1$.

[0069] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0 \leq x \leq 1$, $0 \leq y \leq 1$, and $0 \leq z \leq 1$.

[0070] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.8, y is 0.1, and z is 0.1.

[0071] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.6, y is 0.2, and z is 0.2.

[0072] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.5, y is 0.3, and z is 0.2.

[0073] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 1/3, y is 1/3, and z is 1/3.

[0074] In some examples, including any of the foregoing, the cathode active material is selected from $LiMn_2O_4$, $LiCoO_2$, $Li(NiCoMn)O_2$, and $Li(NiCoAl)O_2$.

[0075] In some examples, set forth herein is a solid-state cathode comprising a coated cathode active material set forth herein.

[0076] In some examples, set forth herein is a coated cathode active material, comprising: a cathode active material and a coating in contact with the cathode active material, wherein the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4 °, 30.3 °, and 31.7 ° (± 0.5 °) (2Θ), when measured using Cu (Kα) radiation at 25 °C; and wherein the peak intensity ratio (k) of the peak at 30.3 ° (2Θ) relative to the peak at 31.7 ° (2Θ) is greater than 1 or less than 2.

[0077] In some examples, including any of the foregoing k is 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, or 1.9. In some examples, including any of the foregoing k is 1.1. In some examples, including any of the foregoing k is 1.2. In some examples, including any of the foregoing k is 1.3. In some examples, including any of the foregoing k is 1.4. In some examples, including any of the foregoing k is 1.5. In some examples, including any of the foregoing k is 1.6. In some examples, including any of the foregoing k is 1.7. In some examples, including any of the foregoing k is 1.8. In some examples, including any of the foregoing k is 1.9.

[0078] In some examples, including any of the foregoing, the coating comprises $Li_{(3-x)}B_{(1-x)}C_xO_3$, wherein $0<x<0.65$. In some examples, x is 0.01. In some examples, x is 0.05. In some examples, x is 0.10. In some examples, x is 0.15. In some examples, x is 0.20. In some examples, x is 0.25. In some examples, x is 0.30. In some examples, x is 0.35. In some examples, x is 0.4. In some examples, x is 0.45. In some examples, x is 0.5. In some examples, x is 0.55. In some examples, x is 0.6 In some examples, x is less than 0.65.

[0079] In some examples, including any of the foregoing, the coating comprises, or further comprises: $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$; $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$; $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$; $Li_xNb_yO_z$, wherein $0.5 \leq x \leq 1.5$, $0.5 \leq y \leq 1.5$, and $2 \leq z \leq 4$; $Li_xTi_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$; $Li_xTi_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$; $Li_xZr_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$; $Li_xZr_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$; $Li_xTi_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$; $Li_xAl_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$; $Li_xY_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$; $Li_xNb_yF_z$, wherein $0.2 \leq x \leq 0.8$, $0.2 \leq y \leq 0.8$, and $1.8 \leq z \leq 4.2$; $Li_xIn_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$; $Li_xAl_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$; $Li_xY_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$; $Li_xFe_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$; $Li_xZr_yCl_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$; $Li_xGe_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$; $Li_xSn_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$; or a combination thereof.

[0080] In some examples, including any of the foregoing, the set forth herein is a coated cathode active material, wherein the coating comprises $Li_{(3-x)}B_{(1-x)}C_xO_3$, wherein $0<x<0.65$.

[0081] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$.

[0082] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$.

[0083] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$.

[0084] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xNb_yO_z$, wherein $0.5 \leq x \leq 1.5$, $0.5 \leq y \leq 1.5$, and $2 \leq z \leq 4$.

[0085] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xTi_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$.

[0086] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xTi_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$.

[0087] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xZr_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$.

[0088] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xZr_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$.

[0089] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xTi_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$.

[0090] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xAl_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$.

[0091] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xY_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$.

[0092] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xNb_yF_z$, wherein $0.2 \leq x \leq 0.8$, $0.2 \leq y \leq 0.8$, and $1.8 \leq z \leq 4.2$.

[0093] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xIn_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$.

[0094] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xAl_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$.

[0095] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xY_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$.

[0096] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xFe_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$.

[0097] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xZr_yCl_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$.

[0098] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xGe_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$.

[0099] In some examples, including any of the foregoing, the coating comprises, or further comprises $Li_xSn_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$.

[0100] In some examples, including any of the foregoing, the coating comprises, or further comprises, Li_2CO_3, Li_3BO_3, $Li_3B_{11}O_{18}$, Li_2ZrO_3, Li_3PO_4, Li_2SO_4, $LiNbO_3$, $Li_4Ti_5O_{12}$, $LiTi_2(PO_4)_3$, $LiZr_2(PO_4)_3$, LiOH, LiF, Li_4ZrF_8, $Li_3Zr_4F_{19}$, Li_3TiF_6, $LiAlF_4$, $LiYF_4$, $LiNbF_6$, ZrO_2, Al_2O_3, TiO_2, ZrF_4, AlF_3, TiF_4, YF_3, NbF_5, or a combination thereof.

[0101] Unless explicitly stated otherwise, the variables herein are chosen so that the chemical formula is charge neutral.

[0102] In some examples, including any of the foregoing, the coating comprises Li_2CO_3, Li_3BO_3, $Li_3B_{11}O_{18}$, $Li_xB_yO_z$, or a combination thereof. In the formula, $Li_xB_yO_z$, $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$.

[0103] In some examples, including any of the foregoing, the coating comprises Li_2CO_3, Li_3BO_3, $Li_3B_{11}O_{18}$, $Li_xB_yO_z$, Li_2ZrO_3, Li_3PO_4, Li_2SO_4, or a combination thereof. In certain examples, the Li_2CO_3 is in contact with the active material. In certain examples, the Li_3BO_3 is in contact with the active material. In certain examples, the $Li_3B_{11}O_{18}$ is in contact with the active material. In certain examples, the LZO is in contact with the active material. In certain examples, the Li_2ZrO_3 is in contact with the active material. In certain examples, the Li_3PO_4 is in contact with the active material. In certain examples, the Li_2SO_4 is in contact with the active material. In certain examples, the $Li_xB_yO_z$ is in contact with the active material.

[0104] In some examples, including any of the foregoing, the coating comprises, or further comprises, Li_2CO_3, Li_3BO_3, $Li_3B_{11}O_{18}$, Li_2ZrO_3, Li_3PO_4, Li_2SO_4, $LiNbO_3$, $Li_4Ti_5O_{12}$, $LiTi_2(PO_4)_3$, $LiZr_2(PO_4)_3$, LiOH, LiF, Li_4ZrF_8, $Li_3Zr_4F_{19}$, Li_3TiF_6, $LiAlF_4$, $LiYF_4$, $LiNbF_6$, ZrO_2, Al_2O_3, TiO_2, ZrF_4, AlF_3, TiF_4, YF_3, NbF_5, or a combination thereof. In certain examples, the coating comprises, or further comprises, Li_2CO_3. In certain examples, the coating comprises, or further comprises, Li_3BO_3. In certain examples, the coating comprises, or further comprises $Li_3B_{11}O_{18}$. In certain examples, the coating comprises, or further comprises, Li_2ZrO_3. In certain examples, the coating comprises, or further comprises, Li_3PO_4.

In certain examples, the coating comprises, or further comprises, Li_2SO_4. In certain examples, the coating comprises, or further comprises, $LiNbO_3$. In certain examples, the coating comprises, or further comprises, $Li_4Ti_5O_{12}$. In certain examples, the coating comprises, or further comprises, $LiTi_2(PO_4)_3$. In certain examples, the coating comprises, or further comprises, $LiZr_2(PO_4)_3$. In certain examples, the coating comprises, or further comprises, LiOH. In certain examples, the coating comprises, or further comprises, LiF. In certain examples, the coating comprises, or further comprises, Li_4ZrF_8. In certain examples, the coating comprises, or further comprises, $Li_3Zr_4F_{19}$. In certain examples, the coating comprises, or further comprises, Li_3TiF_6. In certain examples, the coating comprises, or further comprises, $LiAlF_4$. In certain examples, the coating comprises, or further comprises, $LiYF_4$. In certain examples, the coating comprises, or further comprises, $LiNbF_6$. In certain examples, the coating comprises, or further comprises, ZrO_2. In certain examples, the coating comprises, or further comprises, Al_2O_3. In certain examples, the coating comprises, or further comprises, TiO_2. In certain examples, the coating comprises, or further comprises, ZrF_4. In certain examples, the coating comprises, or further comprises, AlF_3. In certain examples, the coating comprises, or further comprises, TiF_4. In certain examples, the coating comprises, or further comprises, YF_3. In certain examples, the coating comprises, or further comprises, NbF_5.

[0105] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at 18.9, 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7, degrees (2Θ) when measured using Cu (Kα) radiation at 25 °C.

[0106] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, and 31.7 degrees (2Θ) when measured using Cu (Kα) radiation at 25 °C.

[0107] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, and 37.2, degrees (2Θ) when measured using Cu (Kα) radiation at 25 °C.

[0108] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 30.3, 31.7, 33.6, 36.7, and 37.2, degrees (2Θ) when measured using Cu (Kα) radiation at 25 °C.

[0109] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7, degrees (2Θ) when measured using Cu (Kα) radiation at 25 °C.

[0110] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, and 39.8 degrees (2Θ) when measured using Cu (Kα) radiation at 25 °C.

[0111] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 18.9, 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, and 39.8 degrees (2Θ) when measured using Cu (Kα) radiation at 25 °C.

[0112] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7 degrees (2Θ) when measured using Cu (Kα) radiation at 25 °C.

[0113] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 18.9, 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7 degrees (2Θ) when measured using Cu (Kα) radiation at 25 °C.

[0114] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern substantially as shown in FIG. 2.

[0115] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern substantially as shown as Example D in FIG. 2.

[0116] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern substantially as shown in FIG. 6.

[0117] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern substantially as shown in FIG. 7.

[0118] In some examples, including any of the foregoing, the coating comprises Li_3BO_3 and Li_2CO_3, and the molar ratio of $Li_xB_yO_z$ to Li_2CO_3 is greater than 1. In formula, $Li_xB_yO_z$, $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$.

[0119] In some examples, including any of the foregoing, the coating comprises Li_3BO_3 and Li_2CO_3, and the molar ratio of $Li_xB_yO_z$ to Li_2CO_3 is greater than 1 and less than 2.

[0120] In some examples, including any of the foregoing, the coating comprises Li_3BO_3 and Li_2CO_3, and the molar ratio of Li_3BO_3 to Li_2CO_3 is greater than 1.

[0121] In some examples, including any of the foregoing, the coating comprises Li_3BO_3 and Li_2CO_3, and the molar ratio of Li_3BO_3 to Li_2CO_3 is greater than 1 and less than 2.

[0122] In some examples, including any of the foregoing, the coating comprises crystalline Li_3BO_3 and crystalline Li_2CO_3, and the molar ratio of Li_3BO_3 to Li_2CO_3 is greater than 1 and less than 2.

[0123] In some examples, including any of the foregoing, the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn), $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24, $LiMn_2O_4$, $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2, $LiCoO_2$, $Li(NiCoMn)O_2$, $Li(NiCoAl)O_2$, and a nickel cobalt aluminum oxide.

[0124] In some examples, including any of the foregoing, the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn); $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24; $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2; a nickel cobalt aluminum oxide; $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$; and $LiNi_xCo_yAl_zO_2$, wherein $x+y+z=1$, and $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$. In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$. In certain examples, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.8, y is 0.1, and z is 0.1. In certain other examples, the coated cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.6, y is 0.2, and z is 0.2. In some examples, the coated cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.5, y is 0.3, and z is 0.2. In some other examples, the coated cathode active material is $LiNi_xMn_yCo_zO_2$, x is 1/3, y is 1/3, and z is 1/3. In certain examples, the coated cathode active material is selected from $LiMn_2O_4$, $LiCoO_2$, $Li(NiCoMn)O_2$, and $Li(NiCoAl)O_2$.

[0125] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x+y+z=1, $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$. In certain examples, the amount of lithium in the cathode active material will vary depending on the state-of-charge of the battery. For example, the amount of lithium may range from $Li_{0.95-1.1}(Ni_xMn_yCo_z)O_2$, wherein x, y, and z, are as defined above. In certain other examples, the amount of lithium may range from $Li_{0.2-1.1}(Ni_xMn_yCo_z)O_2$, wherein x, y, and z, are as defined above. Other ranges of lithium are contemplated herein.

[0126] Unless explicitly stated otherwise, the variables herein are chose so that the chemical formula is charge neutral.

[0127] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises Li_3BO_3, $Li_3B_{11}O_{18}$, $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0128] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0129] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises Li_3BO_3, $Li_3B_{11}O_{18}$, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0130] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$; $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$; $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$; or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0131] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises Li_3BO_3, $Li_3B_{11}O_{18}$, Li_2ZrO_3, Li_3PO_4, Li_2SO_4, $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0132] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$; $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$; $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$; Li_2SO_4, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0133] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises Li_3BO_3, $Li_3B_{11}O_{18}$, LZO, Li_3PO_4, Li_2SO_4, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0134] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2ZrO_3; the second coating comprises Li_2CO_3, Li_3BO_3, $Li_3B_{11}O_{18}$, Li_3PO_4, Li_2SO_4, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0135] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises LZO; the second coating comprises Li_2CO_3, Li_3BO_3, $Li_3B_{11}O_{18}$, Li_3PO_4, Li_2SO_4, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0136] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2ZrO_3; the second coating comprises Li_3BO_3; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0137] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises LZO; the second coating comprises Li_3BO_3; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0138] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$; $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$; $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$; Li_2SO_4, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0139] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises $Li_2Zr_2O_3$; the second coating comprises $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$; $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$; $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$; Li_2SO_4, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0140] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises LZO; the second coating comprises $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0141] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_3BO_3; the second coating comprises $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$; $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$; $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$; Li_2SO_4, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0142] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$; and the second coating comprises Li_3BO_3; $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$; $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$; Li_2SO_4, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0143] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_3BO_3; the second coating comprises Li_2CO_3, Li_2ZrO_3, $Li_3B_{11}O_{18}$, Li_3PO_4, Li_2SO_4, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0144] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises LZO; the second coating comprises Li_3PO_4; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0145] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2ZrO_3; the second coating comprises Li_3PO_4; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0146] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq$

$z \leq 2.6$; the second coating comprises Li_2SO_4; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0147] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_3BO_3; the second coating comprises Li_2SO_4; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0148] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises Li_2SO_4; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0149] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a coating LZO; and wherein: the coating contacts the cathode active material.

[0150] Also set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a coating Li_2ZrO_3; and wherein: the coating contacts the cathode active material.

[0151] In some examples, including any of the foregoing, the molar ratio of Li_3BO_3 to Li_2CO_3, in the first coating and second coating combined, is greater than 1.

[0152] In some examples, including any of the foregoing, the molar ratio of $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$, to Li_2CO_3, in the first coating and second coating combined, is greater than 1.

[0153] In some examples, including any of the foregoing, the molar ratio of crystalline $Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$, to crystalline Li_2CO_3, in the first coating and second coating combined, is greater than 1 and less than 2.

[0154] In some examples, including any of the foregoing, the molar ratio of Li_3BO_3 to Li_2CO_3, in the first coating and second coating combined, is greater than 1 and less than 2.

[0155] In some examples, including any of the foregoing, the molar ratio of crystalline Li_3BO_3 to crystalline Li_2CO_3, in the first coating and second coating combined, is greater than 1 and less than 2.

[0156] In some examples, including any of the foregoing, the thickness of each coating is about 1 nm to 50 nm. This means that in those examples where a cathode active material has two coatings, each of the two coatings may have a thickness from 1 nm to 50 nm. Each coating may have the same or different thickness as the other coating. In some examples, one of the two coatings has a thickness of 1 nm. In some examples, one of the two coatings has a thickness of 2 nm. In some examples, one of the two coatings has a thickness of 3 nm. In some examples, one of the two coatings has a thickness of 4 nm. In some examples, one of the two coatings has a thickness of 5 nm. In some examples, one of the two coatings has a thickness of 6 nm. In some examples, one of the two coatings has a thickness of 7 nm. In some examples, one of the two coatings has a thickness of 8 nm. In some examples, one of the two coatings has a thickness of 9 nm. In some examples, one of the two coatings has a thickness of 10 nm. In some examples, one of the two coatings has a thickness of 11 nm. In some examples, one of the two coatings has a thickness of 12 nm. In some examples, one of the two coatings has a thickness of 13 nm. In some examples, one of the two coatings has a thickness of 14 nm. In some examples, one of the two coatings has a thickness of 15 nm. In some examples, one of the two coatings has a thickness of 16 nm. In some examples, one of the two coatings has a thickness of 17 nm. In some examples, one of the two coatings has a thickness of 18 nm. In some examples, one of the two coatings has a thickness of 19 nm. In some examples, one of the two coatings has a thickness of 20 nm. In some examples, one of the two coatings has a thickness of 21 nm. In some examples, one of the two coatings has a thickness of 22 nm. In some examples, one of the two coatings has a thickness of 23 nm. In some examples, one of the two coatings has a thickness of 24 nm. In some examples, one of the two coatings has a thickness of 25 nm. In some examples, one of the two coatings has a thickness of 26 nm. In some examples, one of the two coatings has a thickness of 27 nm. In some examples, one of the two coatings has a thickness of 28 nm. In some examples, one of the two coatings has a thickness of 29 nm. In some examples, one of the two coatings has a thickness of 30 nm. In some examples, one of the two coatings has a thickness of 31 nm. In some examples, one of the two coatings has a thickness of 32 nm. In some examples, one of the two coatings has a thickness of 33 nm. In some examples, one of the two coatings has a thickness of 34 nm. In some examples, one of the two coatings has a thickness of 35 nm. In some examples, one of the two coatings has a thickness of 36 nm. In some examples, one of the two coatings has a thickness of 37 nm. In some examples, one of the two coatings has a thickness of 38 nm. In some examples, one of the two coatings has a thickness of 39 nm. In some examples, one of the two coatings has a thickness of 40 nm. In some examples, one of the two coatings has a thickness of 41 nm. In some examples, one of the two coatings has a thickness of 42 nm. In some examples, one of the two coatings has a thickness of 43 nm. In some examples, one of the two coatings has a thickness of 44 nm. In some examples, one of the two coatings has a thickness of 45 nm. In some examples, one of the two coatings has a thickness of 46 nm. In some examples, one of the two coatings has a thickness of 47 nm. In some examples, one of the two coatings has a thickness of 48 nm. In some examples, one of the two coatings has a thickness of 49 nm. In some examples, one of the two coatings has a thickness of 50 nm. In some examples, the second of the two coatings has a thickness of 1 nm. In some examples, the second of the two coatings has a thickness of 2 nm. In some examples, the second of the two coatings has a thickness of 3 nm. In some examples, the second of the two coatings has a thickness of 4 nm. In some examples, the second of the two coatings has a thickness of 5 nm. In some examples, the second of the two coatings has a thickness of 6 nm. In some examples, the second of the two coatings has a thickness of 7 nm. In some examples, the second of the two coatings has a thickness of 8 nm. In some examples, the second of the two coatings has a thickness of 9 nm. In some examples, the second of the two coatings has a thickness of 10 nm. In some examples, the second of the two coatings has a thickness of 11 nm. In some examples, the second of the two coatings has a thickness of 12 nm. In some examples, the second of the two coatings has a thickness of 13 nm. In some examples, the second of the two coatings has a thickness of 14 nm. In some examples, the second of the two coatings has a thickness of 15 nm. In some examples, the second of the two coatings has a thickness of 16 nm. In some examples, the second of the two coatings has a thickness of 17 nm. In some examples, the second of the two coatings has a thickness of 18 nm. In some examples, the second of the two coatings has a thickness of 19 nm. In some examples, the second of the two coatings has a thickness of 20 nm. In some examples, the second of the two coatings has a thickness of 21 nm. In some examples, the second of the two coatings has a thickness of 22 nm. In some examples, the second of the two coatings has a thickness of 23 nm. In some examples, the second of the two coatings has a thickness of 24 nm. In some examples, the second of the two coatings has a thickness of 25 nm. In some examples, the second of the two coatings has a thickness of 26 nm. In some examples, the second of the two coatings has a thickness of 27 nm. In some examples, the second of the two coatings has a thickness of 28 nm. In some examples, the second of the two coatings has a thickness of 29 nm. In some examples, the second of the two coatings has a thickness of 30 nm. In some examples, the second of the two coatings has a thickness of 31 nm. In some examples, the second of the two coatings has a thickness of 32 nm. In some examples, the second of the two coatings has a thickness of 33 nm. In some examples, the second of the two coatings has a thickness of 34 nm. In some examples, the second of the two coatings has a thickness of 35 nm. In some examples, the second of the two coatings has a thickness of 36 nm. In some examples, the second of the two coatings has a thickness of 37 nm. In some examples, the second of the two coatings has a thickness of 38 nm. In some examples, the second of the two coatings has a thickness of 39 nm. In some examples, the second of the two coatings has a thickness of 40 nm. In some examples, the second of the two coatings has a thickness of 41 nm. In some examples, the second of the two coatings has a thickness of 42 nm. In some examples, the second of the two coatings has a thickness of 43 nm. In some examples, the second of the two coatings has a thickness of 44 nm. In some examples, the second of the two coatings has a thickness of 45 nm. In some examples, the second of the two coatings has a thickness of 46 nm. In some examples, the second of the two coatings has a thickness of 47 nm. In some examples, the second of the two coatings has a thickness of 48 nm. In some examples, the second of the two coatings has a thickness of 49 nm. In some examples, the second of the two coatings has a thickness of 50 nm.

[0157] In some examples, including any of the foregoing, the coatings are characterized as having an x-ray powder diffraction (XRD) pattern having peaks at 21.4, 30.3, and 31.7 (± 0.5 °) (2Θ), when measured using Cu (Kα) radiation at 25 °C; and wherein the peak intensity ratio (k) of the peak at 30.3 degree (2Θ) relative to the peak at 31.7 degree (2Θ) is greater than 1 or less than 2.

[0158] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at 18.9, 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7, when measured using Cu (Kα) radiation at 25 °C.

[0159] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, and 31.7 when measured using Cu (Kα) radiation at 25 °C.

[0160] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, and 37.2, when measured using Cu (Kα) radiation at 25 °C.

[0161] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 30.3, 31.7, 33.6, 36.7, and 37.2, when measured using Cu (Kα) radiation at 25 °C.

[0162] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7, when measured using Cu (Kα) radiation at 25 °C.

[0163] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, and 39.8, when measured using Cu (Kα) radiation at 25 °C.

[0164] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 18.9, 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, and 39.8, when measured using Cu (Kα) radiation at 25 °C.

[0165] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7, when measured using Cu (Kα) radiation at 25 °C.

[0166] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 18.9, 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7, when measured using Cu (Kα) radiation at 25 °C.

[0167] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern substantially as shown in FIG. 2.

[0168] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern substantially as shown as Example D in FIG. 2.

[0169] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern substantially as shown in FIG. 6.

[0170] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern substantially as shown in FIG. 7.

[0171] In some examples, set forth herein is a coated cathode active material, comprising: a cathode active material and a coating in contact with the cathode active material, wherein the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4 °, 30.3 °, and 31.7 ° (± 0.5 °) (2Θ), when measured using Cu (Kα) radiation at 25 °C; and wherein the peak intensity ratio (k) of the peak at 30.3 degree (2Θ) relative to the peak at 31.7 °(2Θ) is greater than 1 or less than 2; optionally wherein the coating comprises
$Li_{(3-x)}B_{(1-x)}C_xO_3$, wherein $0<x<0.65$; and wherein the coating comprises, or further comprises a member selected from:

$Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$;

$Li_xC_yO_z$, wherein $0.4 \leq x \leq 1.8$, $0.1 \leq y \leq 1$, and $1 \leq z \leq 1.8$;

$Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$;

$Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$;

$Li_xNb_yO_z$, wherein $0.5 \leq x \leq 1.5$, $0.5 \leq y \leq 1.5$, and $2 \leq z \leq 4$;

$Li_xTi_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xTi_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xZr_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xZr_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xTi_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xAl_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$;

$Li_xY_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$;

$Li_xNb_yF_z$, wherein $0.2 \leq x \leq 0.8$, $0.2 \leq y \leq 0.8$, and $1.8 \leq z \leq 4.2$;

$Li_xIn_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xAl_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xY_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xFe_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xZr_yCl_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xGe_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xSn_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$; or

a combination thereof.

[0172] In some examples, set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the first coating contacts the cathode active material; and the second coating contacts the first coating; the second coating comprises, or further comprises a member selected from:

$Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$;

$Li_xC_yO_z$, wherein $0.4 \leq x \leq 1.8$, $0.1 \leq y \leq 1$, and $1 \leq z \leq 1.8$;

$Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$;

$Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$;

$Li_xNb_yO_z$, wherein $0.5 \leq x \leq 1.5$, $0.5 \leq y \leq 1.5$, and $2 \leq z \leq 4$;

$Li_xTi_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xTi_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xZr_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xZr_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xTi_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xAl_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$;

$Li_xY_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$;

$Li_xNb_yF_z$, wherein $0.2 \leq x \leq 0.8$, $0.2 \leq y \leq 0.8$, and $1.8 \leq z \leq 4.2$; or

a combination thereof.

[0173] In some examples, set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating contacts the cathode active material; and the second coating contacts the first coating; the either the first coating, the second coating, or both, individually in each instance comprises:

$Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$;

$Li_xC_yO_z$, wherein $0.4 \leq x \leq 1.8$, $0.1 \leq y \leq 1$, and $1 \leq z \leq 1.8$;

$Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$;

$Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$;

$Li_xNb_yO_z$, wherein $0.5 \leq x \leq 1.5$, $0.5 \leq y \leq 1.5$, and $2 \leq z \leq 4$;

$Li_xTi_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xTi_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xZr_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xZr_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xTi_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xAl_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$;

$Li_xY_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$;

$Li_xNb_yF_z$, wherein $0.2 \leq x \leq 0.8$, $0.2 \leq y \leq 0.8$, and $1.8 \leq z \leq 4.2$;

$Li_xIn_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xAl_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xY_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xFe_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xZr_yCl_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xGe_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xSn_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$; or

a combination thereof.

[0174] In some examples, including any of the foregoing, the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn), $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24, $LiMn_2O_4$, $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2, $LiCoO_2$, $Li(NiCoMn)O_2$, $Li(NiCoAl)O_2$, and Nickel Cobalt Aluminum Oxides.

[0175] In some examples, including any of the foregoing, the cathode active material comprises $Li_{(3-x)}B_{(1-x)}C_xO_3$, wherein $0<x<0.65$, at the coating or the coating interface.

[0176] In some other examples, set forth herein is a solid-state cathode comprising a coated cathode active material set forth herein.

[0177] In some examples, including any of the foregoing, the solid-state cathode comprises a solid-state electrolyte selected from the group consisting of $Li_2S—SiS_2$, $Li_2S—SiS_2—LiI$, $Li_2S—SiS_2—Li_3MO_4$, $Li_2S—SiS_2—Li_3MO_3$, $Li_2S—P_2S_5—LiI$, and LATS, where M is a member selected from the group consisting of Si, P, Ge, B, Al, Ga, and In.

[0178] In some examples, including any of the foregoing, the solid-state cathode comprises LSTPS or LPSI.

[0179] In some other examples, set forth herein is a battery comprising a solid-state cathode set forth herein, a solid separator and an anode.

[0180] Also set forth herein is a coated cathode active material, comprising: a cathode active material and a coating in contact with the cathode active material, wherein the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 26.2 ° and 27.4 ° (± 0.5 °) (2Θ), when measured using Cu (Kα) radiation at 25 °C.

[0181] In some examples, including any of the foregoing, the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn), $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24, $LiMn_2O_4$, $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2, $LiCoO_2$, $Li(NiCoMn)O_2$, $Li(NiCoAl)O_2$, and a nickel cobalt aluminum oxide.

[0182] In some examples, including any of the foregoing, the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn); $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24; $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2; a nickel cobalt aluminum oxide; $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$; and $LiNi_xCo_yAl_zO_2$, wherein $x+y+z=1$, and $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$. In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x+y+z=1, 0≤x≤1, 0≤y≤1, and 0≤z≤1. In certain examples, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.8, y is 0.1, and z is 0.1. In certain other examples, the coated cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.6, y is 0.2, and z is 0.2. In some other examples, the coated cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.5, y is 0.3, and z is 0.2. In other examples, the coated cathode active material is $LiNi_xMn_yCo_zO_2$, x is 1/3, y is 1/3, and z is 1/3. In some examples, the coated cathode active material is selected from $LiMn_2O_4$, $LiCoO_2$, $Li(NiCoMn)O_2$, and $Li(NiCoAl)O_2$.

[0183] In some examples, including any of the foregoing, the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn); $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24; $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2; a nickel cobalt aluminum oxide; $LiNi_xMn_yCo_zO_2$, x+y+z=1, 0≤x≤1, 0≤y≤1, and 0≤z≤1; and $LiNi_xCo_yAl_zO_2$, wherein x+y+z=1, and 0≤x≤1, 0≤y≤1, and 0≤z≤1.

[0184] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x+y+z=1, 0≤x≤1, 0≤y≤1, and 0≤z≤1.

[0185] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.8, y is 0.1, and z is 0.1.

[0186] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.6, y is 0.2, and z is 0.2.

[0187] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.5, y is 0.3, and z is 0.2.

[0188] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 1/3, y is 1/3, and z is 1/3.

[0189] In some examples, including any of the foregoing, the cathode active material is selected from $LiMn_2O_4$, $LiCoO_2$, $Li(NiCoMn)O_2$, and $Li(NiCoAl)O_2$.

[0190] In some examples, set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises Li_3BO_3, $Li_3B_{11}O_{18}$, or a combination thereof; and wherein: the first coating contacts the cathode active material; and the second coating contacts the first coating.

[0191] In some examples, including any of the foregoing, the molar ratio of Li_3BO_3 to Li_2CO_3, in the first coating and second coating combined, is greater than 1.

[0192] In some examples, including any of the foregoing, the molar ratio of Li_3BO_3 to Li_2CO_3, in the first coating and second coating combined, is greater than 1 and less than 2.

[0193] In some examples, including any of the foregoing, the molar ratio of crystalline Li_3BO_3 to crystalline Li_2CO_3, in the first coating and second coating combined, is greater than 1 and less than 2.

[0194] In some examples, including any of the foregoing, the coatings are characterized as having an x-ray powder diffraction (XRD) pattern having peaks at 21.4, 30.3, and 31.7 (± 0.5 °) (2Θ), when measured using Cu (Kα) radiation at 25 °C; and wherein the peak intensity ratio (k) of the peak at 30.3 degree (2Θ) relative to the peak at 31.7 degree (2Θ) is greater than 1 or less than 2.

[0195] In some examples, set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the second coating comprises $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$; $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$; or $Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$.

[0196] In some examples, including any of the foregoing, the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn), $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24, $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2, and nickel cobalt aluminum oxides.

[0197] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$.

[0198] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.8, y is 0.1, and z is 0.1.

[0199] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.6, y is 0.2, and z is 0.2.

[0200] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.5, y is 0.3, and z is 0.2.

[0201] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 1/3, y is 1/3, and z is 1/3.

[0202] In some examples, including any of the foregoing, the cathode active material is selected from $LiMn_2O_4$, $LiCoO_2$, $Li(NiCoMn)O_2$, and $Li(NiCoAl)O_2$.

[0203] In some examples, including any of the foregoing, the cathode active material comprises $Li_{(3-x)}B_{(1-x)}C_xO_3$, wherein $0 \leq x \leq 0.65$, at the coating or the coating interface.

[0204] In some other examples, set forth herein is a solid-state cathode comprising a coated cathode active material set forth herein.

[0205] In some examples, including any of the foregoing, the solid-state cathode further comprises a solid-state electrolyte selected from the group consisting of $Li_2S—SiS_2$, $Li_2S—SiS_2—LiI$, $Li_2S—SiS_2—Li_3MO_4$, $Li_2S—SiS_2—Li_3MO_3$, $Li_2S—P_2S_5—LiI$, and LATS, where M is a member selected from the group consisting of Si, P, Ge, B, Al, Ga, and In.

[0206] In some examples, including any of the foregoing, the solid electrolyte comprises LSTPS or LPSI.

[0207] In certain examples, set forth herein is a battery comprising a solid-state cathode, set forth herein, a solid separator and an anode.

[0208] In certain examples, set forth herein is a coated cathode active material, comprising: a cathode active material and a coating in contact with the cathode active material, wherein the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 26.2 ° and 27.4 ° (± 0.5 °) (2Θ), when measured using Cu (Kα) radiation at 25 °C.

[0209] In some examples, including any of the foregoing, the coating comprises Li_3BO_3 and Li_2CO_3.

[0210] In some examples, including any of the foregoing, the coating comprises Li_2ZrO_3 and Li_3PO_4.

[0211] In some examples, including any of the foregoing, the Li_2ZrO_3 is in contact with the active material.

[0212] In some examples, including any of the foregoing, the coating comprises Li_3BO_3 and Li_2SO_4.

[0213] In some examples, including any of the foregoing, the Li_3BO_3 is in contact with the active material.

[0214] In some examples, including any of the foregoing, the coating comprises Li_2CO_3 and Li_2SO_4.

[0215] In some examples, including any of the foregoing, the Li_2CO_3 is in contact with the active material.

[0216] In some examples, including any of the foregoing, the coating comprises Li_2ZrO_3.

[0217] In some examples, including any of the foregoing, the Li_2ZrO_3 is in contact with the active material.

[0218] In some examples, including any of the foregoing, the thickness of each coating is about 1 nm to 50 nm.

[0219] In some examples, set forth herein is a coated cathode active material, comprising: a cathode active material and a coating in contact with the cathode active material, wherein the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4 °, 30.3 °, and 31.7 ° (± 0.5 °) (2Θ), when measured using Cu (Kα) radiation at 25 °C; and wherein the peak intensity ratio (k) of the peak at 30.3 degree (2Θ) relative to the peak at 31.7 degree (2Θ) is greater than 1 or less than 2; optionally wherein the coating comprises $Li_{(3-x)}B_{(1-x)}C_xO_3$, wherein $0<x<0.65$; and wherein the coating comprises, or further comprises:

$Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$;

$Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$;

$Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$;

$Li_xNb_yO_z$, wherein $0.5 \leq x \leq 1.5$, $0.5 \leq y \leq 1.5$, and $2 \leq z \leq 4$;

$Li_xTi_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xTi_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xZr_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xZr_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xTi_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xAl_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$;

$Li_xY_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$;

$Li_xNb_yF_z$, wherein $0.2 \leq x \leq 0.8$, $0.2 \leq y \leq 0.8$, and $1.8 \leq z \leq 4.2$;

$Li_xIn_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xAl_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xY_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xFe_yCl_z$, wherein $0.5 \leq x \leq 1$, $0 \leq y \leq 0.5$, and $1 \leq z \leq 2$;

$Li_xZr_yCl_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xGe_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xSn_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$; or

a combination thereof.

[0220] In some examples, set forth herein is a coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating comprises Li_2CO_3; the first coating contacts the cathode active material; and the second coating contacts the first coating; the second coating comprises, or further comprises:

$Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$;

$Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$;

$Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$;

$Li_xNb_yO_z$, wherein $0.5 \leq x \leq 1.5$, $0.5 \leq y \leq 1.5$, and $2 \leq z \leq 4$;

$Li_xTi_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xTi_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xZr_yP_wO_z$, wherein $0 \leq x \leq 2$, $1 \leq y \leq 3$, $1 \leq w \leq 4$, and $2 \leq z \leq 20$;

$Li_xZr_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xTi_yF_z$, wherein $0.2 \leq x \leq 0.75$, $0.25 \leq y \leq 0.8$, and $1.75 \leq z \leq 3.4$;

$Li_xAl_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$;

$Li_xY_yF_z$, wherein $0.4 \leq x \leq 0.8$, $0.2 \leq y \leq 0.6$, and $1.4 \leq z \leq 2.2$;

$Li_xNb_yF_z$, wherein $0.2 \leq x \leq 0.8$, $0.2 \leq y \leq 0.8$, and $1.8 \leq z \leq 4.2$; or a combination thereof.

[0221] A coated cathode active material, comprising: a cathode active material; wherein: the cathode active material comprises a first coating and a second coating; the first coating contacts the cathode active material; and the second coating contacts the first coating; the either the first coating, the second coating, or both, individually in each instance comprises:

$Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$;

$Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;

$Li_xP_yO_z$, wherein $0.6 \le x \le 1.5$, $0.5 \le y \le 1.4$, and $2.0 \le z \le 3.7$;

$Li_xZr_y(PO_4)_z$, wherein $0.05 \le x \le 1.5$, $1 \le y \le 3$, and $2.0 \le z \le 4.0$;

$Li_xNb_yO_z$, wherein $0.5 \le x \le 1.5$, $0.5 \le y \le 1.5$, and $2 \le z \le 4$;

$Li_xTi_yO_z$, wherein $0 \le x \le 1.6$, $0.2 \le y \le 1.0$, and $2 \le z \le 1.2$;

$Li_xTi_yP_wO_z$, wherein $0 \le x \le 2$, $1 \le y \le 3$, $1 \le w \le 4$, and $2 \le z \le 20$;

$Li_xZr_yP_wO_z$, wherein $0 \le x \le 2$, $1 \le y \le 3$, $1 \le w \le 4$, and $2 \le z \le 20$;

$Li_xZr_yF_z$, wherein $0.2 \le x \le 0.75$, $0.25 \le y \le 0.8$, and $1.75 \le z \le 3.4$;

$Li_xTi_yF_z$, wherein $0.2 \le x \le 0.75$, $0.25 \le y \le 0.8$, and $1.75 \le z \le 3.4$;

$Li_xAl_yF_z$, wherein $0.4 \le x \le 0.8$, $0.2 \le y \le 0.6$, and $1.4 \le z \le 2.2$;

$Li_xY_yF_z$, wherein $0.4 \le x \le 0.8$, $0.2 \le y \le 0.6$, and $1.4 \le z \le 2.2$;

$Li_xNb_yF_z$, wherein $0.2 \le x \le 0.8$, $0.2 \le y \le 0.8$, and $1.8 \le z \le 4.2$;

$Li_xIn_yCl_z$, wherein $0.5 \le x \le 1$, $0 \le y \le 0.5$, and $1 \le z \le 2$;

$Li_xAl_yCl_z$, wherein $0.5 \le x \le 1$, $0 \le y \le 0.5$, and $1 \le z \le 2$;

$Li_xY_yCl_z$, wherein $0.5 \le x \le 1$, $0 \le y \le 0.5$, and $1 \le z \le 2$;

$Li_xFe_yCl_z$, wherein $0.5 \le x \le 1$, $0 \le y \le 0.5$, and $1 \le z \le 2$;

$Li_xZr_yCl_z$, wherein $0.2 \le x \le 0.75$, $0.25 \le y \le 0.8$, and $1.75 \le z \le 3.4$;

$Li_xGe_yP_wO_z$, wherein $0 \le x \le 2$, $1 \le y \le 3$, $1 \le w \le 4$, and $2 \le z \le 20$;

$Li_xSn_yP_wO_z$, wherein $0 \le x \le 2$, $1 \le y \le 3$, $1 \le w \le 4$, and $2 \le z \le 20$;

or a combination thereof.

[0222] In some examples, including any of the foregoing, the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn); $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24; $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2; a nickel cobalt aluminum oxide; $LiNi_xMn_yCo_zO_2$, x+y+z=1, 0≤x≤1, 0≤y≤1, and 0≤z≤1; and $LiNi_xCo_yAl_zO_2$, wherein x+y+z=1, and 0≤x≤1, 0≤y≤1, and 0≤z≤1.

[0223] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x+y+z=1, 0≤x≤1, 0≤y≤1, and 0≤z≤1.

[0224] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.8, y is 0.1, and z is 0.1.

[0225] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.6, y is 0.2, and z is 0.2.

[0226] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.5, y is 0.3, and z is 0.2.

[0227] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 1/3, y is 1/3, and z is 1/3.

[0228] In some examples, including any of the foregoing, the cathode active material is selected from $LiMn_2O_4$, $LiCoO_2$, $Li(NiCoMn)O_2$, and $Li(NiCoAl)O_2$.

PROCESS FOR MAKING

[0229] FIG. 1 illustrates some of the differences between certain new methods and compositions disclosed herein and those in the following citations: Literature 1 is *Chem. Mater.* 2018, 30, 22, 8190–8200,(https://doi.org/10.1021/acs.chemmater.8b03321. Literature 2 is *Adv. Energy Mater.* 2020, 1903778 (https://doi.org/10.1002/aenm.201903778). Literature 3 is *Journal of Power Sources* Volume 248, 15 February 2014, Pages 943-950 (https://doi.org/10.1016/j.jpowsour.2013.10.005).

[0230] Certain disclosed herein result in more uniform coverage of the cathode active material. This results in a more stable interface between the cathode active material and the solid-state electrolyte which is included in the cathode with the cathode active material.

[0231] Also set forth herein is a process for making a coated cathode active material, comprising the following steps: coating a cathode active material with a solution of LiOH; removing the solvent from the solution coating the cathode active material to provide a first material; annealing the first material under dry air conditions to form an annealed first material; coating the annealed first material with a solution of LiOH and a boron source to form a second material; and annealing the second material to form a coated cathode active material.

[0232] Also set forth herein is a process for making a coated cathode active material, comprising the following steps: coating a cathode active material with a solution of LiOH and a boron source; removing the solvent from the solution coating the cathode active material to provide a coated cathode active material; and annealing the coated cathode active material under dry air conditions to form a coated cathode active material.

[0233] In some examples, including any of the foregoing, a source of boron includes, but is not limited to H_3BO_3. In some examples, including any of the foregoing, a source of boron includes, but is not limited to a boron-containing compound which is soluble in methanol.

[0234] In some examples, including any of the foregoing, a source of LiOH includes, but is not limited to LiOH. In some examples, including any of the foregoing, a source of LiOH includes, but is not limited to a lithium-containing compound which is soluble in methanol.

[0235] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at 18.9, 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7, when measured using Cu (Kα) radiation at 25 °C.

[0236] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, and 31.7 when measured using Cu (Kα) radiation at 25 °C.

[0237] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, and 37.2, when measured using Cu (Kα) radiation at 25 °C.

[0238] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 30.3, 31.7, 33.6, 36.7, and 37.2, when measured using Cu (Kα) radiation at 25 °C.

[0239] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7, when measured using Cu (Kα) radiation at 25 °C.

[0240] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, and 39.8 when measured using Cu (Kα) radiation at 25 °C.

[0241] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 18.9, 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, and 39.8 when measured using Cu (Kα) radiation at 25 °C.

[0242] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7, when measured using Cu (Kα) radiation at 25 °C.

[0243] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern having peaks at least at 18.9, 21.4, 30.3, 31.7, 33.6, 36.7, 37.2, 39.8, 44.1, 44.9, and 48.7, when measured using Cu (Kα) radiation at 25 °C.

[0244] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern substantially as shown in FIG. 2.

[0245] In some examples, including any of the foregoing, the coating is characterized as having an x-ray powder diffraction (XRD) pattern substantially as shown as Example D in FIG. 2.

[0246] In some examples, including any of the foregoing, the annealing is at a temperature of at most 350 °C for at least 10 minutes.

[0247] In some examples, including any of the foregoing, the annealing is at a temperature of at most 350 °C for at least 10 minutes.

[0248] In some examples, including any of the foregoing, the solvent is methanol.

[0249] In certain examples, set forth herein is a process for making a coated cathode active material, comprising the following operations: coating a cathode active material with a solution of LiOH; removing the solvent from the solution coating the cathode active material to provide a first material; heating the first material under dry air conditions to form a heated first material; coating the heated first material with a solution of LiOH and a boron source to form a second material; and heating the second material to form a coated cathode active material.

[0250] In some examples, including any of the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn); $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24; $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2; a nickel cobalt aluminum oxide; $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$; and $LiNi_xCo_yAl_zO_2$, wherein $x+y+z=1$, and $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$.

[0251] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$.

[0252] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.8, y is 0.1, and z is 0.1.

[0253] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.6, y is 0.2, and z is 0.2.

[0254] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.5, y is 0.3, and z is 0.2.

[0255] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 1/3, y is 1/3, and z is 1/3.

[0256] In some examples, including any of the foregoing, the cathode active material is selected from $LiMn_2O_4$, $LiCoO_2$, $Li(NiCoMn)O_2$, and $Li(NiCoAl)O_2$.

[0257] In certain examples, set forth herein is a process for making a coated cathode active material, comprising the following operations: coating a cathode active material with a solution of LiOH and a boron source; removing the solvent from the solution coating the cathode active material to provide a coated cathode active material; and heating the coated cathode active material under dry air conditions to form a coated cathode active material.

[0258] In some examples, including any of the foregoing, the heating is at a temperature of at most 350 °C for at least 10 minutes.

[0259] In some examples, including any of the foregoing, the heating is at a temperature of at most 350 °C for at least 10 minutes.

[0260] In some examples, including any of the foregoing, the solvent is methanol.

[0261] In some examples, including any of the foregoing, the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn); $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24; $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2; a nickel cobalt aluminum oxide; $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$; and $LiNi_xCo_yAl_zO_2$, wherein $x+y+z=1$, and $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$.

[0262] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0\leq x\leq 1$, $0\leq y\leq 1$, and $0\leq z\leq 1$.

[0263] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.8, y is 0.1, and z is 0.1.

[0264] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.6, y is 0.2, and z is 0.2.

[0265] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.5, y is 0.3, and z is 0.2.

[0266] In some examples, including any of the foregoing, the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 1/3, y is 1/3, and z is 1/3.

[0267] In some examples, including any of the foregoing, the cathode active material is selected from $LiMn_2O_4$, $LiCoO_2$, $Li(NiCoMn)O_2$, and $Li(NiCoAl)O_2$.

EXAMPLES

[0268] Reagents, chemicals, and materials were commercially purchased unless specified otherwise to the contrary.

[0269] Pouch cell containers were purchased from Showa Denko.

[0270] The Electrochemical potentiostat used was an Arbin potentiostat.

[0271] Electrical impedance spectroscopy (EIS) was performed with a Biologic VMP3, VSP, VSP-300, SP- 150, or SP-200.

[0272] Electron microscopy was performed in a FEI Quanta SEM, a Helios 600i, or a Helios 660 FIB-SEM.

[0273] Transmission Electron microscopy was performed as follows.

[0274] Sample preparation: The samples for TEM measurements were prepared using Ga ion sourced focused ion beam (nanoDUE'T NB5000, Hitachi High-Technologies). To protect the surface of material from the Ga ion beam, multiple protective layers were deposited in advance to the sampling; at first, metal layer was deposited by plasma coater and then carbon protective layer and tungsten layer were deposited by high vacuum evaporation and focused ion beam, respectively. The thin slice sampling was conducted by focused ion beam. The prepared sample was measured in TEM.

[0275] TEM measurement: TEM images of coated NMC were obtained by field emission electron microscope (JEM-2100F, JEOL). The Acceleration voltage was set to 200kV. The electron beam radius was set to about 0.7 to 1 nm.

[0276] X-ray powder diffraction (XRD) was performed in a Bruker D8 Advance A25 with Cu K-α radiation at room temperature (*e.g.*, between 21 °C and 23 °C). Source is Cu-Ka, wavelength at 1.54 Å. X-ray at 40.kV and 25 mA. Detector: LYNXEYE_XE with PSD opening 2.843. Divergence slit at 0.6mm and antiscatter at 5.0mm fixed.

[0277] Milling was performed using a Retsch PM 400 Planetary Ball Mill. Mixing was performed using a Fischer Scientific vortex mixer, a Flaktek speed mixer, or a Primix filmix homogenizer.

[0278] Casting was performed on a TQC drawdown table. Calendering was performed on an IMC calender.

[0279] Light scattering was performed on a Horiba, model: Partica, Model No.: LA-950V2, general term: laser scattering particle size distribution analyzer.

[0280] The Lithium Nickel Cobalt Manganese Oxide (NMC) used in the Examples was $LiNi_{0.85}Co_{0.1}Mn_{0.05}O_2$ unless specified otherwise.

EXAMPLE 1 – PREPARATION OF NMC COATED WITH Li_3BO_3 AND ANNEALED AT 250 °C

[0281] **Step 1: Coating solution preparation**

[0282] A coating solution was prepared by combining 0.600g of LiOH (Spectrum Chemical) with 0.515g of H_3BO_3 (Sigma) into 400g of methanol (Sigma). This mixture was stirred for twelve hours at 45 °C in an argon (Ar) filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0283] **Step 2: Coating step**

[0284] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) (40g) was put into the solution prepared in step 1 (400g) and stirred for 0.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0285] **Step 3: Annealing step**

[0286] The powder obtained from step 2 was heated under dry air at 250 °C for 1 hour. This resulted in the coated cathode material.

[0287] *See* FIG. 2 for an XRD pattern of the coated cathode material.

EXAMPLE 2 – PREPARATION OF NMC COATED WITH Li_2CO_3 AND Li_3BO_3 AND ANNEALED AT 250 °C

[0288] **Step 1: Coating solution preparation**

[0289] A coating solution was prepared by placing 0.07 g of LiOH (Spectrum Chemical) in 400g of methanol (Sigma). This mixture was stirred for 12 hours at 45 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0290] **Step 2: Coating step**

[0291] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) (40g) was put into the solution prepared in step 1 (400g) and stirred for 0.5 hours. After stirring, the power was dried using a rotary evaporator at 65 °C to remove the solution.

[0292] **Step 3: Annealing step**

[0293] The powder obtained from step 2 was heated under dry air at 250 °C for 1 hour. This resulted in a coated cathode material having a first coating of Li_2CO_3 in contact with the active material.

[0294] The powder obtained from precursor solution in step 1 was also heated at 250 °C for 1 hour so its x-ray diffraction pattern could be observed.

[0295] *See* FIG. 2 for an XRD pattern of the coated cathode material.

[0296] **Step 4: Coating solution preparation**

[0297] A coating solution was prepared by combining 0.194 g of LiOH (Spectrum Chemical) with 0.167 g of H_3BO_3 (Sigma) into 400g of methanol (Sigma). This mixture was stirred for 12 hours at 45 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0298] **Step 5: Coating step**

[0299] The Li_2CO_3-coated Lithium Nickel Cobalt Manganese Oxide (NMC) powder (prepared in step 3) (40g), from step 3, was put into the solution prepared in step 4 (400g) and stirred for 0.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0300] **Step 6: Annealing step**

[0301] The powder obtained from step 5 was heated under dry air at 250 °C for 1 hour. This resulted in a coated cathode material having a first coating of Li_2CO_3 in contact with the active material and a second coating of Li_3BO_3 in contact with the first coating.

[0302] The powder obtained from precursor solution in step 1 was also heated at 250 °C for 1 hour so its x-ray diffraction pattern could be observed.

[0303] *See* FIG. 2 for an XRD pattern of the coated cathode material.

EXAMPLE 3 – PREPARATION OF NMC COATED WITH LZO /Li_3BO_3 AND ANNEALED AT 250 °C

[0304] **Step 1: Coating solution preparation**

[0305] A coating solution was prepared by placing 0.10 g of LiOH (Spectrum Chemical) and Zirconium butoxide 80% solution (sigma) 0.96mL in 400g of ethanol (Sigma). This mixture was stirred for twelve hours at 45 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0306] **Step 2: Coating step**

[0307] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) (40g) was put into the solution prepared in step 1 (400g) and stirred for 0.5 hours, follow by adding DI water (0.11 mL). The solution was stirred for another 1.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0308] **Step 3: Annealing step**

[0309] The powder obtained from step 2 was heated under clean dry air at 375 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material.

[0310] The powder obtained from the precursor solutions in step 1 and 2 was also heated at 375°C for 1 hour so its x-ray diffraction pattern could be observed.

[0311] **Step 4: Coating solution preparation**

[0312] A coating solution was prepared by combining 0.285g of LiOH (Spectrum Chemical) with 0.25g of H_3BO_3 (Sigma) into 400g of methanol (Sigma). This mixture was stirred for 12 hours at 45 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0313] **Step 5: Coating step**

[0314] The LZO-coated Lithium Nickel Cobalt Manganese Oxide (NMC) powder (prepared in step 3) (40g) was put into the solution prepared in step 4 (400g) and stirred for

0.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0315] **Step 6: Annealing step**

[0316] The powder obtained from step 5 was heated under dry air at 250 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material and a second coating of Li_3BO_3 (LBO) in contact with the first coating.

[0317] Transmission electron microscope shows clear two layers of LZO/LBO on the top of NMC. *See* FIG. 5.

EXAMPLE 4 – PREPARATION OF NMC COATED WITH LZO /Li_3PO_4 USING SOLID-STATE REACTION AND ANNEALED AT 375 °C

[0318] **Step 1: Coating solution preparation**

[0319] A coating solution was prepared by placing 0.10 g of LiOH (Spectrum Chemical) and Zirconium butoxide 80% solution (sigma) 0.96mL in 400g of ethanol (Sigma). This mixture was stirred for 12 hours at 45 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 <$ 0.1 ppm).

[0320] **Step 2: Coating step**

[0321] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) (40g) was put into the solution prepared in step 1 (400g) and stirred for 0.5 hours, follow by adding 0.11 milliliters (mL) DI water. The solution was stirred for another 1.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0322] **Step 3: Annealing step**

[0323] The powder obtained from step 2 was heated under clean dry air at 375 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material.

[0324] **Step 4: Solid-State Reaction**

[0325] A secondary coating layer was prepared with a solid-state reaction. The powders obtained by step 3 was mixed with 0.173g of $NH_4H_2PO_4$ for 10 min in an agate mortar in an Ar filled Glove box.

[0326] **Step 5: Annealing step**

[0327] The powder obtained from step 4 was heated under dry air at 250 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material and a second coating of Li_3PO_4 (LPO) in contact with the first coating.

EXAMPLE 5 – PREPARATION OF NMC COATED WITH LZO/Li_3PO_4 USING A SOLID-STATE REACTION AT HIGHER CONCENTRATION THAN EXAMPLE 4 AND ANNEALED AT 375 °C

[0328] **Step 1: Coating solution preparation**

[0329] A coating solution was prepared by placing 0.10 g of LiOH (Spectrum Chemical) and Zirconium butoxide 80% solution (sigma) 0.96mL in 400g of ethanol (Sigma). This mixture was stirred for 12 hours at 45 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0330] **Step 2: Coating step**

[0331] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) (40g) was put into the solution prepared in step 1 (400g) and stirred for 0.5 hours, follow by adding distilled water (DI) water 0.11mL.

[0332] The solution was stirred for another 1.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0333] **Step 3: Annealing step**

[0334] The powder obtained from step 2 was heated under clean dry air at 375 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material.

[0335] **Step 4: Coating solution preparation**

[0336] Secondary coating layer was prepared with solid state reaction. The powders obtained by step 3 was mixed with 0.345g of $NH_4H_2PO_4$ for 10 min in an agate mortar in an Ar filled Glove box.

[0337] **Step 5: Annealing step**

[0338] The powder obtained from step 4was heated under dry air at 250 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material and a second coating of Li_3PO_4 in contact with the first coating.

EXAMPLE 6 – PREPARATION OF NMC COATED WITH Li_3BO_3/ Li_2SO_4 AND ANNEALED AT 250°C

[0339] **Step 1: Coating solution preparation**

[0340] A coating solution was prepared by combining 0.285g of LiOH (Spectrum Chemical) with 0.25g of H_3BO_3 (Sigma) into 400g of methanol (Sigma). This mixture was stirred for 12 hours at 45 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0341] Stoichiometric amounts of distilled water was added to the solution. The solution was dried to get powder precursors.

[0342] **Step 2: Coating step**

[0343] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) (40g) was put into the solution prepared in step 1 (400g) and stirred for 0.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0344] **Step 3: Annealing step**

[0345] The powder obtained from step 2 was heated under clean dry air at 250 °C for 1 hour. This resulted in a coated cathode material having a first coating of Li_3BO_3 in contact with the active material.

[0346] **Step 4: Coating solution preparation**

[0347] A coating solution was prepared by putting 0.02 mL of H_2SO_4 (95%, aqueous) into 400g of ethanol (Sigma). This mixture was stirred for 12 hours at 20 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0348] **Step 5: Coating step**

[0349] The Li_3BO_3-coated Lithium Nickel Cobalt Manganese Oxide (NMC) powder (prepared in step 3) (40g) was put into the solution prepared in step 4 (400g) and stirred for 0.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0350] **Step 6: Annealing step**

[0351] The powder obtained from step 5 was heated under dry air at 250 °C for 1 hour. This resulted in a coated cathode material having a first coating of Li_3BO_3 in contact with the active material and a second coating of Li_2SO_4 in contact with the first coating.

EXAMPLE 7 – PREPARATION OF NMC COATED WITH Li_2CO_3/ Li_2SO_4 AND ANNEALED AT 250°C

[0352] **Step 1: Coating solution preparation**

[0353] A coating solution was prepared by combining 0.1g of LiOH (Spectrum Chemical) into 400g of methanol (Sigma). This mixture was stirred for 12 hours at 45 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0354] Stoichiometric amounts of distilled water was added to the solution. The solution was dried to get powder precursors.

[0355] **Step 2: Coating step**

[0356] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) (40g) was put into the solution prepared in step 1 (400g) and stirred for 0.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0357] **Step 3: Annealing step**

[0358] The powder obtained from step 2 was heated under clean dry air at 250 °C for 1 hour. This resulted in a coated cathode material having a first coating of Li_2CO_3 in contact with the active material.

[0359] **Step 4: Coating solution preparation**

[0360] A coating solution was prepared by putting 0.02 mL of H_2SO_4 (95%, aqueous) into 400g of ethanol (Sigma). This mixture was stirred for 12 hours at 20 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0361] **Step 5: Coating step**

[0362] The Li_3BO_3-coated Lithium Nickel Cobalt Manganese Oxide (NMC) powder (prepared in step 3) (40g) was put into the solution prepared in step 4 (400g) and stirred for 0.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0363] **Step 6: Annealing step**

[0364] The powder obtained from step 5 was heated under dry air at 250 °C for 1 hour. This resulted in a coated cathode material having a first coating of Li_2CO_3 in contact with the active material and a second coating of Li_2SO_4 in contact with the first coating.

EXAMPLE 8 – PREPARATION OF NMC COATED WITH LZO/Li_3PO_4 USING AN ACID TREATMENT, AT HIGH CONCENTRATION, AND ANNEALED AT 375 °C

[0365] **Step 1: Coating solution preparation**

[0366] A coating solution was prepared by placing 0.10 g of LiOH (Spectrum Chemical) and Zirconium butoxide 80% solution (sigma) 0.96mL in 400g of ethanol (Sigma). This mixture was stirred for 12 hours at 45 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 <$ 0.1 ppm).

[0367] Stoichiometric amounts of distilled water was added to the solution. The solution was dried to get powder precursors.

[0368] **Step 2: Coating step**

[0369] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) (40g) was put into the solution prepared in step 1 (400g) and stirred for 0.5 hours, follow by adding DI water 0.11 mL. The solution was stirred for another 1.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0370] **Step 3: Annealing step**

[0371] The powder obtained from step 2 was heated under clean dry air at 375 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material.

[0372] **Step 4: Coating solution preparation**

[0373] A coating solution was prepared by putting 0.2 mL of H_3PO_4 (85%, aqueous) into 400g of ethanol (Sigma). This mixture was stirred for 12 hours at 20 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0374] **Step 5: Coating step**

[0375] The LZO-coated Lithium Nickel Cobalt Manganese Oxide (NMC) powder (prepared in step 3) (40g) was put into the solution prepared in step 5 (400g) and stirred for 0.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0376] **Step 6: Annealing step**

[0377] The powder obtained from step 5 was heated under dry air at 250 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material and a second coating of Li_3PO_4 in contact with the first coating.

EXAMPLE 9 – PREPARATION OF NMC COATED WITH LZO/Li_3PO_4 USING AN ACID TREATMENT, AT LOW CONCENTRATION, AND ANNEALED AT 375 °C

[0378] **Step 1: Coating solution preparation**

[0379] A coating solution was prepared by placing 0.10 g of LiOH (Spectrum Chemical) and Zirconium butoxide 80% solution (sigma) 0.96 mL in 400g of ethanol

(Sigma). This mixture was stirred for 12 hours at 45 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0380] Stoichiometric amounts of distilled water was added to the solution. The solution was dried to get powder precursors.

[0381] **Step 2: Coating step**

[0382] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) (40g) was put into the solution prepared in step 1 (400g) and stirred for 0.5 hours, follow by adding DI water 0.11 mL. The solution was stirred for another 1.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0383] **Step 3: Annealing step**

[0384] The powder obtained from step 2 was heated under clean dry air at 375 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material.

[0385] **Step 4: Coating solution preparation**

[0386] A coating solution was prepared by putting 0.02 mL of H_3PO_4 (85%, aqueous) into 400g of ethanol (Sigma). This mixture was stirred for 12 hours at 20 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0387] **Step 5: Coating step**

[0388] The LZO-coated Lithium Nickel Cobalt Manganese Oxide (NMC) powder (prepared in step 3) (40g) was put into the solution prepared in step 5 (400g) and stirred for 0.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0389] **Step 6: Annealing step**

[0390] The powder obtained from step 5 was heated under dry air at 250 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material and a second coating of Li_3PO_4 in contact with the first coating.

EXAMPLE 10 – PREPARATION OF NMC COATED WITH LZO USING A SPRAY DRYER AND ANNEALED AT 375 °C

[0391] Step 1: Coating solution preparation

[0392] A coating solution was prepared by placing 19.45 g of $LiOCH_3$ and 11.98g of $Zr(OC_3H_7)_4$ in 781g of isopropanol. This mixture was stirred for 12 hours at 25 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm).

[0393] Step 2: Coating step

[0394] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) 500g was put into the solution prepared in step 1 (781g) and stirred for 0.5 hours.

[0395] The coating was prepared by using a spray drying method. The coating solution was carried and atomized in a hot drying chamber (120 °C), which allowed for the evaporation of the solvent in the solution and the formation of solid particles. N_2 was used as carrier gas to atomize a liquid stream of the coating solution. The liquid stream of the coating solution produces particles which pass through a cyclone and are collected in a holding chamber.

[0396] Step 3: Annealing step

[0397] The powder obtained from step 3 was heated under clean dry air at 375 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material.

EXAMPLE 11 – PREPARATION OF NMC COATED WITH LZO AND ANNEALED AT 375 °C

[0398] Step 1: Coating solution preparation

[0399] A coating solution was prepared by adding 0.375 g LiOH and 3.57 mL Zirconium butoxide ($Zr(OBu)_4$) to 1000 mL anhydrous ethanol. The solution was allowed to stir overnight at room temperature under Argon.

[0400] Step 2: Coating step

[0401] In a dry room, 150 g of Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) was added to the coating solution of Step 1. The resulting mixture was allowed to stir for 30 minutes. 0.425 mL of distilled water was added dropwise to solution to initiate the sol-gel reaction. The reaction proceeded under stirring for more than one and a half hours. After stirring stopped, the solution was decanted and the active material dried using a Rotovap at 65 °C, using a sonicating water bath.

[0402] **Step 3: Annealing step**

[0403] The powder obtained from step 3 was heated in an alumina or quartz crucible under flowing clean dry air (CDA, 250 sccm) at 375 °C for 1 hour. This resulted in a coated cathode material having a first coating comprising LZO in contact with the active material. An x-ray diffraction pattern of an LZO coating is shown in FIG. 6. Additional amorphous phases may be present in the coating given that an x-ray diffraction pattern primarily provides information about crystalline materials.

EXAMPLE 12 – PREPARATION OF SOLID ELECTROLYTES

[0404] A first solid electrolyte was prepared. $Li_{10}Si_{0.5}Sn_{0.5}P_2S_{12}$ (hereinafter “LSTPS”) was wet milled to produce LSTPS particles having a d_{50} particle diameter of about 50 nm to 500 nm. In this Example, LSTPS is referred to a compound characterized by the formula $Li_{10}Si_{0.5}Sn_{0.5}P_2S_{12}$. See US Patent Nos. 9,172,114 and 10,535,878, which are herein incorporated by reference in their entirety for all purposes.

[0405] A second solid electrolyte was prepared: Lithium sulfide (Li_2S), phosphorus pentasulfide (P_2S_5), and lithium iodide (LiI) were mixed in a predetermined ratio. In one sample, lithium sulfide (Li_2S), phosphorus pentasulfide (P_2S_5), and lithium iodide (Lil) were mixed. The molar ratio of $LiI:Li_2S:P_2S_5$ was (3 to 4):(0.1 to l):(0.5 to 1.5). The mixture was placed in a 500 ml zirconia milling jar with 1 mm zirconia milling media at a milling media:powder mass ratio of >7.5. The mixture was agitated in a planetary mill (Retsch PM400, 150 mm revolution radius, 1:2 speed ratio) for sixteen to thirty-six 16-32 hours.

[0406] This procedure was performed in an Ar filled glovebox (H_2O < 0.1ppm, O_2 < 0.1ppm).

EXAMPLE 13 – MAKING A BATTERY CELL

[0407] Battery cell fabrication was performed in an Ar filled glovebox (H_2O < 0.1ppm, O_2 < 0.1ppm).

[0408] A cathode layer was made by mixing the coated NMC material from one of Examples 1-11 with the first solid electrolyte from Example 12.

[0409] An all-solid-state battery was made using a cathode layer mentioned in the preceding paragraph and a separator which was made of the second solid electrolyte from Example 12.

[0410] The cathode layer and separator were pressed at 700MPa to densify the two into a pellet type battery. An aluminum current collector was used adjacent to the cathode layer. A nickel current collector was used adjacent to an anode layer. The anode layer was made of lithium metal. Metallic lithium as anode was plated when the battery cell was charged.

EXAMPLE 14 – TESTING A BATTERY

[0411] This Example tested the stability of the batteries made according to Example 13.

[0412] Stability testing was performed in an Ar filled glovebox (H_2O < 0.1ppm, O_2 < 0.1ppm).

[0413] Battery cells were charged and discharged at 30 °C at the constant current density of 0.4 mA/cm^2 and within the operation voltage of 3 V to 4.2 V. During discharge, the area-specific resistance (ASR) of the battery cells was obtained by reading voltage drop during relaxation steps. The obtained ASR was named as R_1 here.

[0414] After cycling at 30 °C, the temperature was raised to 60 °C. After the temperature stabilized at 60 °C, the battery cells were again charged to 4.2V with a current density of 0.4 mA/cm^2. Battery cells were held at 4.2V for 3 days, then the cells were discharged to 3V.

[0415] The battery cells' temperature was lowered to 30 °C. The battery cells were charged and discharged between 3 V and 4.2 V and at a current density of 0.4 mA/cm^2. From this, an ASR (R_2) was determined.

[0416] The stability was evaluated by $\Delta R=R_2-R_1$.

[0417] A battery made using the coated cathode active material of Example 11 was tested as noted in this Example. This battery showed a 30 °C dcASR growth of 15 Ωcm^2 .

[0418] A battery made using the coated cathode active material of Example 11 was similarly tested as noted in this Example but at -15 °C. This battery showed a Electrochemical Impedance Spectroscopy at - 15 °C impedance growth of 590 Ωcm^2. The following data was also collected

Difference in initial ASR^2 from control (ohm*cm^2)	Difference in final ASR^2 from control (ohm*cm^2)	Difference in ASR^2 growth from control (ohm*cm^2)
+10	-730	-740

EXAMPLE 15 – PREPARATION OF NMC COATED WITH LZP AND ANNEALED AT 375 °C

[0001] **Step 1: Coating solution preparation**

[0002] A coating solution was prepared by placing 0.031 g of LiOH (Spectrum Chemical), Zirconium butoxide 80% solution (sigma) 1.18mL and 0.274g of P_2O_5 (sigma) in 263g of ethanol (Sigma). This mixture was stirred for 12 hours at 45 °C in an Ar filled glovebox (H_2O < 0.1 ppm, O_2 < 0.1 ppm).

[0003] **Step 2: Coating step**

[0004] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) (50g) was put into the solution prepared in step 1 (263g) and stirred for 1.5 hours.

After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0005] Step 3: Annealing step

[0006] The powder obtained from step 2 was heated under clean dry air at 375 °C for 1 hour. This resulted in a coated cathode material having LZP coating in contact with the active material. Herein LZP is $LiZr_2(PO_4)_3$.

[0007] Transmission electron microscope shows clear two layers of LZP on the top of NMC. *See* FIG. 8.

EXAMPLE 16 – PREPARATION OF NMC COATED WITH LZO/Li_3InCl_6 AND ANNEALED AT 250 °C

[0008] Step 1: Coating solution preparation

[0009] A coating solution was prepared by placing 0.10 g of LiOH (Spectrum Chemical) and Zirconium butoxide 80% solution (sigma) 0.96mL in 400g of ethanol (Sigma). This mixture was stirred for 12 hours at 45 °C in an Ar filled glovebox ($H_2O < 0.1$ ppm, $O_2 <$ 0.1 ppm).

[0010] Step 2: Coating step

[0011] Lithium Nickel Cobalt Manganese Oxide (NMC) powder (purchased from BASF) (40g) was put into the solution prepared in step 1 (400g) and stirred for 0.5 hours, followed by adding deionized water (DI) water (0.11 mL). The solution was stirred for another 1.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0012] Step 3: Annealing step

[0013] The powder obtained from step 2 was heated under clean dry air at 375 °C for 1 hour. This resulted in a coated cathode material having a first coating of LZO in contact with the active material.

[0014] Step 4: Coating chemical preparation

[0015] The coating chemical (Li_3InCl_6) was prepared by high energy ball-milling solid-state synthesis. 1.6956 g of LiCl (sigma) and 2.9491 g of $InCl_3$ (sigma) were loaded into a 125 ml ZrO_2 ball-milling jar with 40 ZrO_2 balls in a diameter of 10 mm in an Ar-filled glovebox ($H_2O < 0.1$ ppm, $O_2 < 0.1$ ppm). This mixture was milled at a speed of 1200 rpm for 5 hours with under a controlled temperature no higher than 50°C using emax (Retsch). The resulting powder was collected in the Ar-filled glovebox, followed by a heat treatment in Ar at 300°C for 5 hours.

[0016] **Step 5: Coating solution preparation**

[0017] A coating solution was prepared by combining 0.3479g of heat treated Li_3InCl_6 (prepared in step 4) into 400g of methanol (Sigma). This mixture was stirred for 10 minutes at 25 °C in ambient air.

[0018] **Step 6: Coating step**

[0019] The Lithium Nickel Cobalt Manganese Oxide (NMC) powder (prepared in step 3) (25 g) was put into the solution prepared in step 5 (400g) and stirred for 0.5 hours. After stirring, the powder was dried using a rotary evaporator at 65 °C to remove the solution.

[0020] **Step 7: Annealing step**

[0021] The powder obtained from step 6 was heated under vacuum at 250 °C for 10 hours. This resulted in a coated cathode material having a first coating of LZO in contact with the active material and a second coating of Li_3InCl_6 in contact with the first coating. Herein, LZO is Li_2ZrO_3.

EXAMPLE 17 – TESTING A BATTERY

[0419] A series of battery cells were prepared as detailed in Table 1. Table 1 specifies the ratio of starting materials, the mass of coated cathode materials, and the annealing temperature.

Table 1

Sample	NMC wt. (g)	Annealing T (°C)	Precursors for coating solution							
			LiOH (g)	$LiOCH_3$ (g)	H_3BO_3 (g)	ZrBuOt (g)	$Zr(OC_3H_7)_4$ (g)	$NH_4H_2PO_4$ (g)	85% H_3PO_4 aq(mL)	95% H_2SO_4 aq (mL)
Example A	40	250	0.600	0	0.515	0	0	0	0	0
Example B	80	200	0.600	0	0.515	0	0	0	0	0
Example C	40	350	0.600	0	0.515	0	0	0	0	0
Example D	40	250	0.07	0	0	0	0	0	0	0
	40	250	0.194	0	0.167	0	0	0	0	0
Comparative Example E	40	600	0.600	0	0.515	0	0	0	0	0
Comparative Example F	40	350	0.296	0	2.805	0	0	0	0	0
Comparative Example G	40	375	0.374	0	0	3.569	0	0	0	0
Example 3	40	375	0.1	0	0	0.95	0	0	0	0
		250	0.285	0	0.25	0	0	0	0	0
Example 4	40	375	0.1	0	0	0.95	0	0	0	0
		250	0	0	0	0	0	0.173	0	0
Example	40	375	0.1	0	0	0.95	0	0	0	0

5	40	250	0	0	0	0	0	0.345	0	0
Example 6	40	250	0.285	0	0.25	0	0	0	0	0
	40	250	0	0	0	0	0	0	0	0.02
Example 7	40	250	0.1	0	0	0	0	0	0	0
	40	250	0	0	0	0	0	0	0	0.02
Example 8	40	375	0.1	0	0	0.95	0	0	0	0
	40	250	0	0	0	0	0	0	0.2	0
Example 9	40	375	0.1	0	0	0.95	0	0	0	0
	40	250	0	0	0	0	0	0	0.02	0
Example 10	500	375	0	19.45	0	0	11.98	0	0	0

[0420] In Table 1, above, Examples D, 3, 4, 5, 6, 7, 8, 9, and 10 were run, separately, at two different temperatures. This is indicated by the double rows in Table 1, above, next to these Examples.

[0421] Herein, the difference between Example A and Example E is the annealing temperature.

[0422] Example B - Li_3BO_3 heated at 200 °C. Made according to Table 1 and Example 1.

[0423] Example C - Li_3BO_3 heated at 350 °C. Made according to Table 1 and Example 1.

[0424] Example D - Li_2CO_3 - Li_3BO_3 dual coating heated at 250 °C. Made according to Table 1 and Example 2.

[0425] Comparative Example E - Li_3BO_3 heated at 600 °C. Made according to Table 1 and Example 1 except that it was heated at 600 °C not 250 °C, as in Example 1. Example E is a reproduction of a synthesis in Chem. Mater. 2018, 30, 22, 8190–8200,(https://doi.org/10.1021/acs.chemmater.8b03321.

[0426] Comparative Example F - $Li_3B_{11}O_{18}$ heated at 350 °C. Made according to Table 1 and Example 1 except that it was heated at 350 °C not 250 °C, as in Example 1.

Example F is a reproduction of *Adv. Energy Mater.* 2020, 1903778 (https://doi.org/10.1002/aenm.201903778).

[0427] Comparative Example G - LZO heated at 375 °C. Made according to Table 1 heated in dry air at 375 °C. Example G is a reproduction of *Journal of Power Sources*, Volume 248, 15 February 2014, Pages 943-950 (https://doi.org/10.1016/j.jpowsour.2013.10.005).

[0428] The results herein, (*e.g.*, Examples 3) demonstrate that the stability of the cathode active material was dramatically improved when a layer of $LiBO_3$ was added on top of a layer of LZO; when compared to an uncoated cathode active material. See, for example, comparative example G.

[0429] The results herein (*e.g.*, Example 10, spray dried LZO) demonstrate that the stability of the cathode active material was improved when LZO was spray dried onto the cathode active material as compared to when the LZO was applied using sol-gel coating techniques and rotary evaporation. See comparative Example 10. The spray dryer may in some instances result in a more uniform coating. For dual coating applications, spray drying may advantageous.

[0430] The results herein (*e.g.*, Examples 3, 8) demonstrate that the stability performance of the dual coating depends on the process by which it is made.

Stability test results

[0431] FIG. 3 shows charge and discharge curves of cells in Example 14.

[0432] Examples A, B, C, and D show a smaller polarization at the 4.2V hold at 60 °C for 3 days than those of the comparative examples. This indicates greater stability of Examples A, B, C, and D, compared to Comparative Examples E, F, and G

[0433] ΔR is an indicator of stability.

[0434] ΔR values are shown in FIG. 4.

[0435] Cell resistance values are listed in Table 2, below.

[0436] In the Examples A, B, C, and D, the ΔR values ranged from 19 to 86.

[0437] In Comparative Examples E, F, and G, the ΔR values ranged from 178 to 356.

X-ray diffraction (XRD)

[0438] The powder from step 1 of Example 1 was obtained and heated at different temperatures.

[0439] FIG. 2 is the XRD patterns of Example A, B, C, D and Comparative Example E.

[0440] Comparative Example E is a reproduction of the Li_3BO_3-Li_2CO_3 material in *Chem. Mater.* 2018, 30, 22, 8190–8200. In Chem. Mater. 2018, 30, 22, 8190–8200, the material was heated at 600 °C. This high temperature cause shrinkage of the coating layer and non-uniform coverage. In addition, unstable phases were observed after high temperature annealing. These unstable phases resulted in poor stability.

[0441] The difference between Examples A, B, and C and Comparative Example E are the following.

[0442] The peak width of the main phase of the new embodiment is much broader than literature condition. This peak width indicates more amorphous material and/or a less dense state. This amorphous material and/or a less dense state is preferred for uniform coatings. For example, if a coating is too crystalline, there could be a densification of the coating and this would result in less coverage.

[0443] The peak intensity difference varies with annealing temperature. This is due to the difference in the ratio of Li_3BO_3 and Li_2CO_3 in the coating chemistry.

[0444] The peak intensity ratio (k) at 30.3 degree (2Θ) and 31.7 degree (2Θ) is as follows: $k= I (30.3) / I (31.7) > 1$ for the new embodiment. $k<1$ in *Chem. Mater.* 2018, 30, 22, 8190–8200.

[0445] k indicates the ratio of Li_3BO_3 and Li_2CO_3. The larger k, the more Li_3BO_3.

[0446] Example A was observed to have a k value of 1.85.

[0447] Example B was observed to have a k value of 1.25.

[0448] Example C was observed to have a k value of 1.27.

[0449] Comparative Example E was observed to have a k value of 0.89.

[0450] This is an indication of a more stable phase and better coverage for Examples A, B, and C, as compared to Comparative Example E.

[0451] Comparative Example F used the $Li_3B_{11}O_{18}$ material from Adv. Energy Mater. 2020, 1903778. This material has a low lithium content which results in high ASR.

[0452] Comparative Example G is a reproduction of the Li_2O–ZrO_2 material from Journal of Power Sources 248, 2014, 943-950. Due to poor stability of the Li-Zr-O system, batteries that use this material are observed to have a high ASR which increases when at a charged state.

[0453] Comparative Examples F and G show higher ΔR than each of Examples A, B, C, or D. This is likely due to $Li_3B_{11}O_{18}$ and Li_2ZrO_3, which are less stable than Examples A, B, C, or D.

[0454] Referring to FIG. 2, the main phase identified is a phase comprising Li, B, C and O. This is marked with diamonds in FIG. 2.

[0455] The crystallinity increased as the annealing temperature increased.

[0456] At 600 °C (Comparative Example E; made according to Chem. Mater. 2018, 30, 22, 8190–8200,(https://doi.org/10.1021/acs.chemmater.8b03321)), the material was a highly crystalline phase of Li-B-C-O with secondary phases also present.

[0457] Poor stability was shown in stability test for Comparative Example E. This indicates that secondary phases may not be stable. Too much crystallinity may cause densification of the coating (because of the higher density of crystals compared to amorphous material) and result in a non-uniform coating.

[0458] The crystallinity decreased as the annealing temperature decreased. The lower density of amorphous materials may result in a more uniform coating. Also, less secondary phases were observed at lower annealing temperature as compared to Comparative Example E.

Table 2

Sample	R1 / Ωcm^2	R2 / Ωcm^2	ΔR / Ωcm^2
Example A	40	91	51
Example B	57	104	47
Example C	45	131	86
Example D	32	51	19
Comparative Example E	54	410	356
Comparative Example F	59	237	178
Comparative Example G	36	339	303
Example 3	42	60	18
Example 4	79	226	147
Example 5	76	385	309
Example 6	61	-	-
Example 7	-	-	-
Example 8	-	-	-
Example 9	97	383	286
Example 10	53	219	166
Example 15	28	53	25
Example 16	69	96	27

[0459] The embodiments and examples described above are intended to be merely illustrative and non-limiting. Those skilled in the art will recognize or will be able to ascertain using no more than routine experimentation, numerous equivalents of specific compounds, materials and procedures. All such equivalents are considered to be within the scope and are encompassed by the appended claims.

CLAIMS

What is claimed is:

1. A composition comprising:
   a cathode active material; and a
   coating in contact with the cathode active material, wherein:
      the coating comprises lithium, carbon, oxygen, zirconium, phosphorus, or a combination thereof;
      the coating is amorphous based on x-ray diffraction pattern analysis;
      the coating comprises crystalline domains based on transmission electron microscopy (TEM) analysis.

2. The composition of claim 1, wherein the coating has the chemical formula:
   $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$;
   $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$;
   $Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$; or
   $Li_xC_yO_z$, wherein $0.4 \leq x \leq 1.8$, $0.1 \leq y \leq 1$, and $1 \leq z \leq 1.8$.

3. The composition of claim 1-2, wherein the coating further comprises amorphous domains based on TEM analysis in addition to the crystalline domains based on transmission electron microscopy analysis.

4. The composition of claim 3, wherein the crystalline domains are in contact with the cathode active material.

5. The composition of claim 4, wherein the amorphous domains are not in contact with the cathode active material.

6. The composition of any one of claims 1-5, wherein the coating has a thickness, T, as determined by TEM analysis, that is $1 \text{ nm} \leq T \leq 20 \text{ nm}$.

7. The composition of claim 82, wherein T is about 1, about 5 nm, or about 10 nm.

8. The composition of any one of claims 1-5, wherein the coating crystalline domains do not lattice match the crystalline domains of the cathode active material, as determined by TEM analysis.

9. The composition of any one of claims 1-8, further comprising a second coating in contact with the coating.

10. The composition of claim 9, wherein the second coating has a chemical formula which is not the same as the chemical formula of the coating.

11. The composition of any one of claims 9-10, wherein the second coating has the chemical formula:

$Li_xB_yO_z$, wherein $0.2 \leq x \leq 0.75$, $0.5 \leq y \leq 1.6$, and $1.5 \leq z \leq 2.6$; or

$Li_xIn_yCl_z$, wherein $2 \leq x \leq 4$, $0 \leq y \leq 2$, and $5 \leq z \leq 7$.

12. The composition of any one of claims 9-11, wherein the second coating is amorphous as determined by TEM analysis.

13. The composition of any one of claims 9-11, wherein the second coating is crystalline as determined by TEM analysis.

14. The composition of any one of claims 9-13, wherein the second coating is Li_3BO_3.

15. The composition of any one of claims 9-13, wherein the coating is Li_3InCl_6.

16. The composition of any one of claims 9-13, wherein the first coating is $Li_xZr_yO_z$, wherein $0 \leq x \leq 1.6$, $0.2 \leq y \leq 1.0$, and $2 \leq z \leq 1.2$.

17. The composition of claim 16, wherein the first coating is a lithium zirconium oxide.

18. The composition of claim 16 or 17, wherein the first coating is a Li_2ZrO_3.

19. The composition of any one of claims 1-18, wherein the first coating is $Li_xP_yO_z$, wherein $0.6 \leq x \leq 1.5$, $0.5 \leq y \leq 1.4$, and $2.0 \leq z \leq 3.7$.

20. The composition of claim 19, wherein the first coating is $Li_3(PO_4)$.

21. The composition of any one of claims 1-10, wherein the first coating is $Li_xZr_y(PO_4)_z$, wherein $0.05 \leq x \leq 1.5$, $1 \leq y \leq 3$, and $2.0 \leq z \leq 4.0$.

22. The composition of claim 21, wherein the first coating is $LiZr_2(PO_4)_3$

23. The composition of any one of claims 1-10, wherein the coating or the second coating, or both, further comprises a member selected from the group consisting of Li_2CO_3, Li_3BO_3, $Li_3B_{11}O_{18}$, Li_2ZrO_3, Li_3PO_4, Li_2SO_4, $LiNbO_3$, $Li_4Ti_5O_{12}$, $LiTi_2(PO_4)_3$, $LiZr_2(PO_4)_3$, LiOH, LiF, Li_4ZrF_8, $Li_3Zr_4F_{19}$, Li_3TiF_6, $LiAlF_4$, $LiYF_4$, $LiNbF_6$, ZrO_2, Al_2O_3, TiO_2, ZrF_4, AlF_3, TiF_4, YF_3, NbF_5, and combinations thereof.

24. The composition of any one of claims 1-23, wherein the cathode active material is selected from $LiMPO_4$ (M=Fe, Ni, Co, Mn); $Li_xTi_yO_z$, wherein x is from 0 to 8, y is from 1 to 12, z is from 1 to 24; $LiMn_{2a}Ni_aO_4$, wherein a is from 0 to 2; a nickel cobalt aluminum oxide; $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0 \leq x \leq 1$, $0 \leq y \leq 1$, and $0 \leq z \leq 1$; and $LiNi_xCo_yAl_zO_2$, wherein $x+y+z=1$, and $0 \leq x \leq 1$, $0 \leq y \leq 1$, and $0 \leq z \leq 1$.

25. The composition of claim 24, wherein the cathode active material is $LiNi_xMn_yCo_zO_2$, $x+y+z=1$, $0 \leq x \leq 1$, $0 \leq y \leq 1$, and $0 \leq z \leq 1$.

26. The composition of claim 24, wherein the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.8, y is 0.1, and z is 0.1.

27. The composition of claim 24, wherein the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.6, y is 0.2, and z is 0.2.

28. The composition of claim 24, wherein the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 0.5, y is 0.3, and z is 0.2.

29. The composition of claim 24, wherein the cathode active material is $LiNi_xMn_yCo_zO_2$, x is 1/3, y is 1/3, and z is 1/3.

30. The composition of claim 24, wherein the cathode active material is selected from $LiMn_2O_4$, $LiCoO_2$, $Li(NiCoMn)O_2$, and $Li(NiCoAl)O_2$.

31. A solid-state cathode comprising the coated cathode active material of any one of claims 1-30.

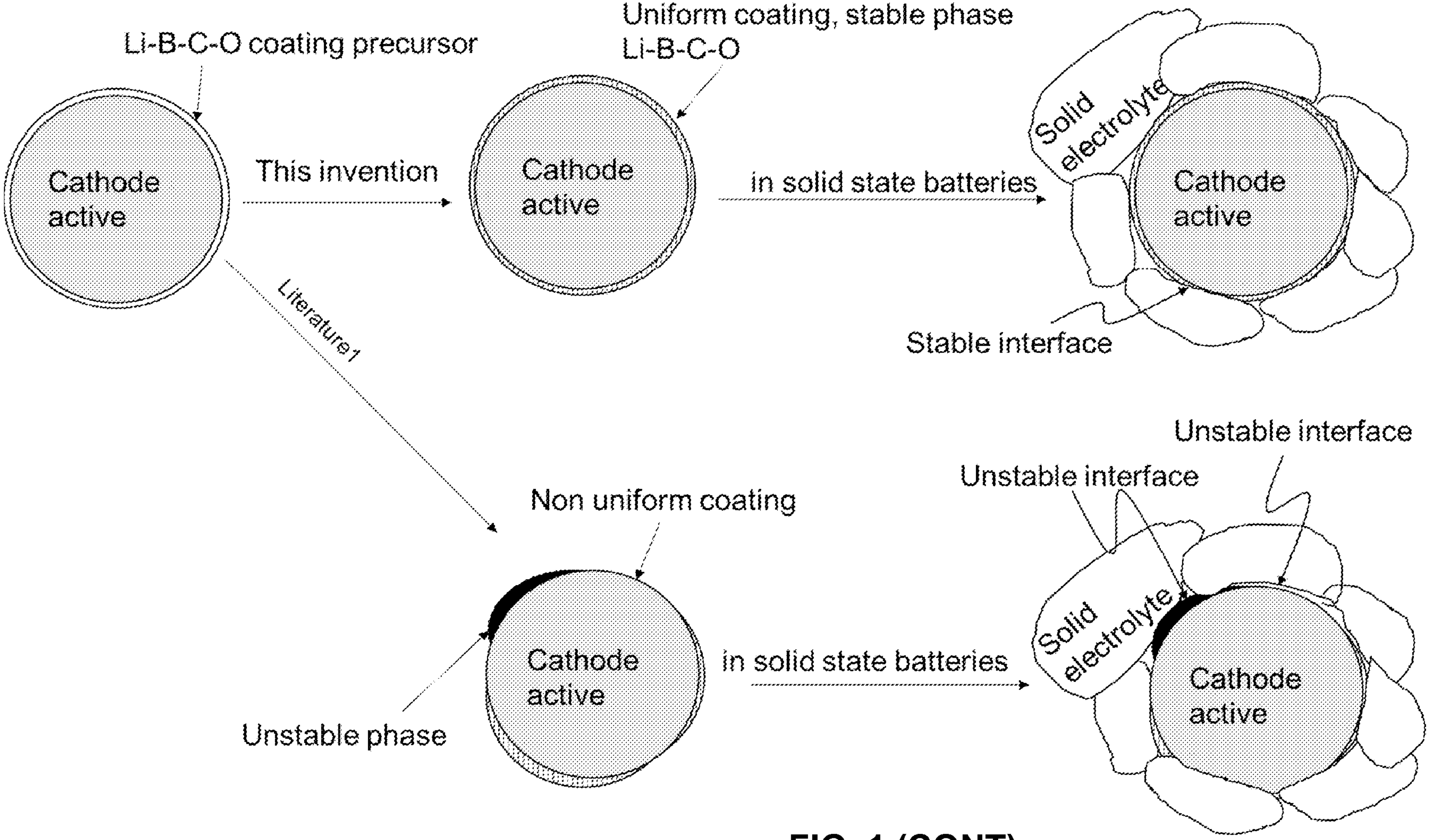
Li-B-C-O coating precursor
Cathode active
This invention
Literature1
Uniform coating, stable phase
Li-B-C-O
Cathode active
in solid state batteries
Solid electrolyte
Cathode active
Stable interface
Non uniform coating
Unstable phase
Cathode active
in solid state batteries
Unstable interface
Unstable interface
Solid electrolyte
Cathode active

FIG. 1 (CONT)

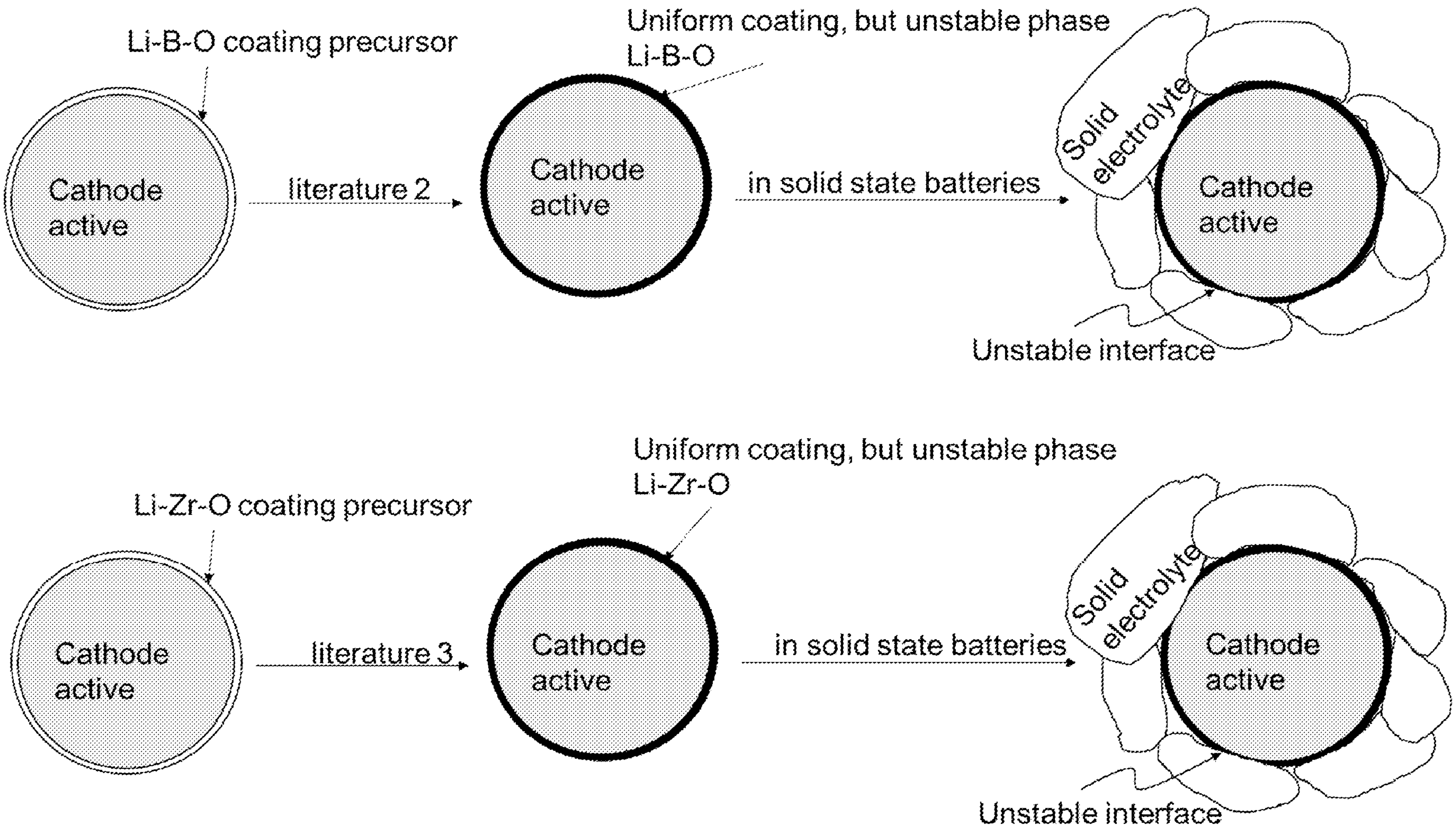
Li-B-O coating precursor
Cathode active
literature 2
Uniform coating, but unstable phase
Li-B-O
Cathode active
in solid state batteries
Solid electrolyte
Cathode active
Unstable interface
Li-Zr-O coating precursor
Cathode active
literature 3
Uniform coating, but unstable phase
Li-Zr-O
Cathode active
in solid state batteries
Solid electrolyte
Cathode active
Unstable interface

FIG. 1

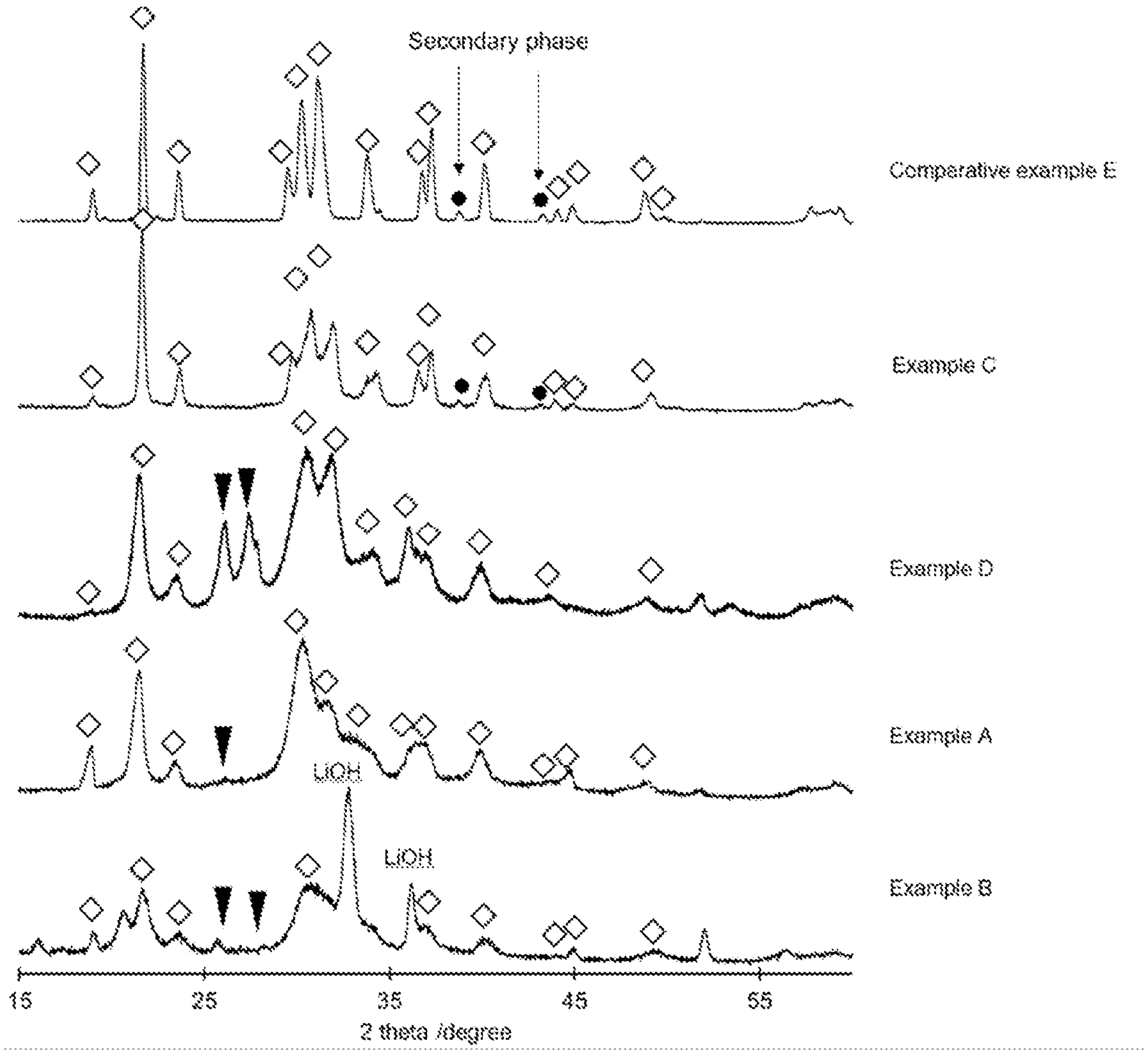
Secondary phase
Comparative example E
Example C
Example D
Example A
LiOH
LiOH
Example B
15
25
35
45
55
2 theta /degree

FIG. 2

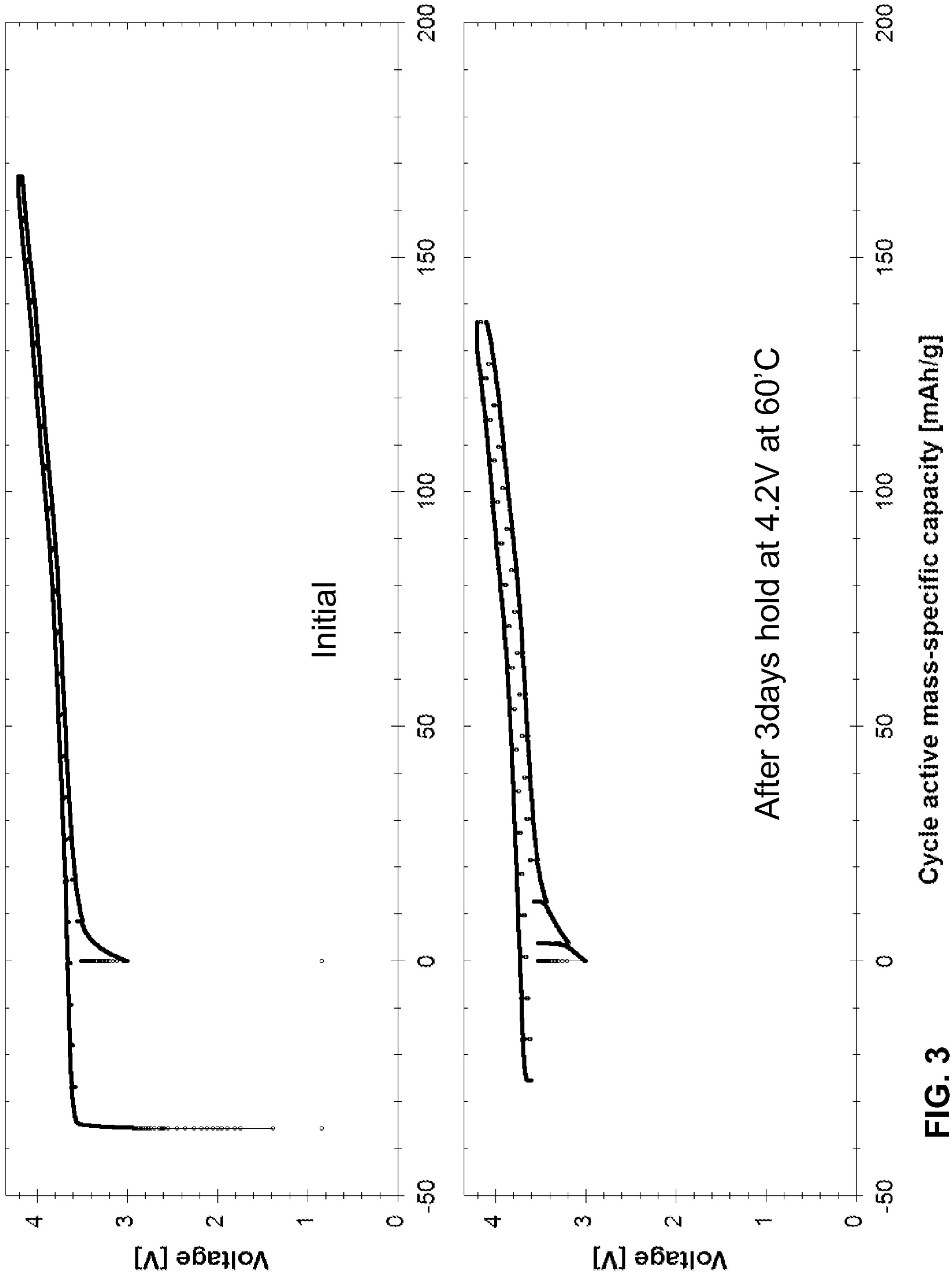
Voltage [V]
0
1
2
3
4
-50
0
50
100
150
200
Initial
After 3days hold at 4.2V at 60˚C
Cycle active mass-specific capacity [mAh/g]

FIG. 3

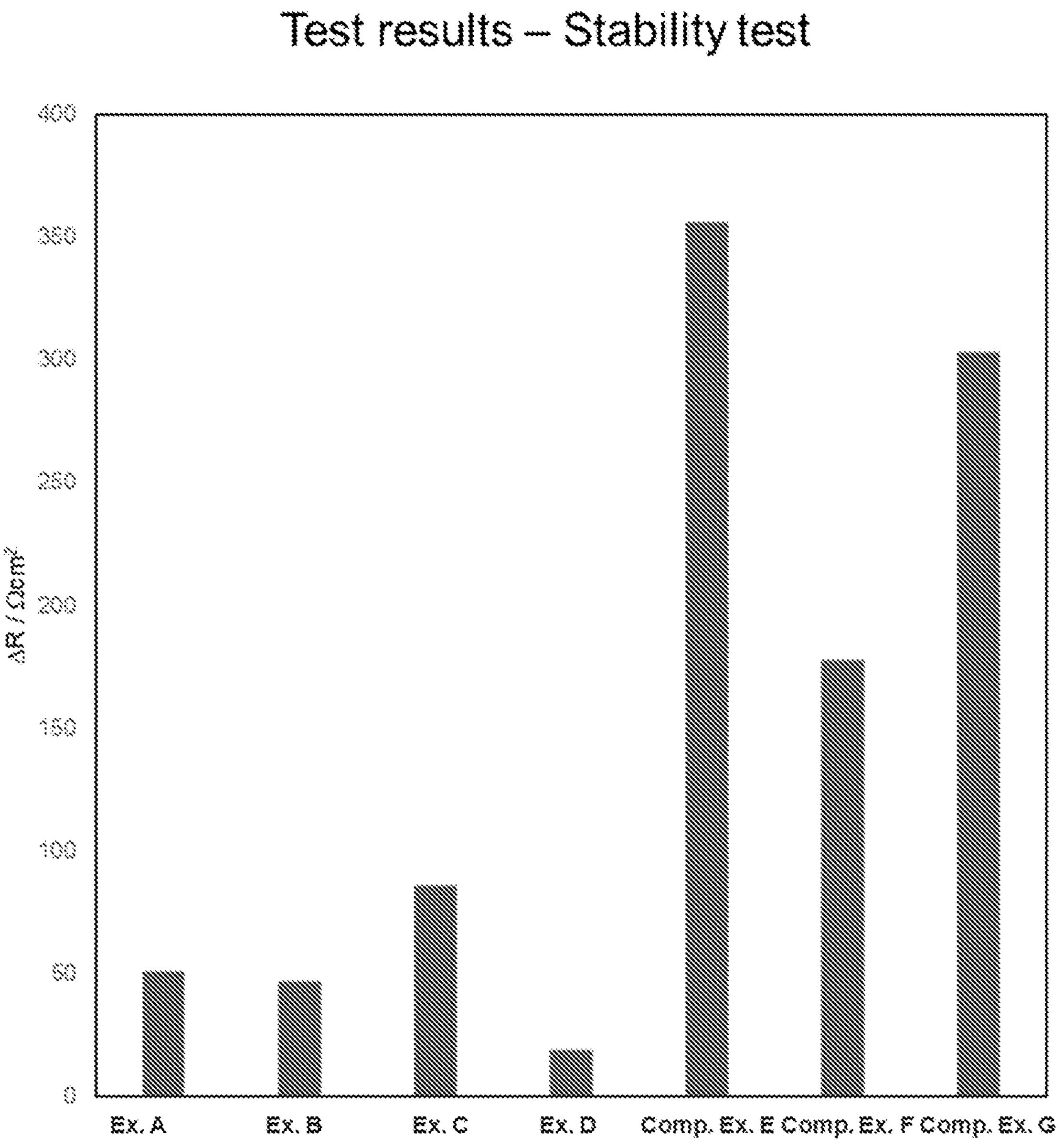
Test results – Stability test
ΔR / Ωcm²
400
350
300
250
200
150
100
50
0
Ex. A
Ex. B
Ex. C
Ex. D
Comp. Ex. E
Comp. Ex. F
Comp. Ex. G

FIG. 4

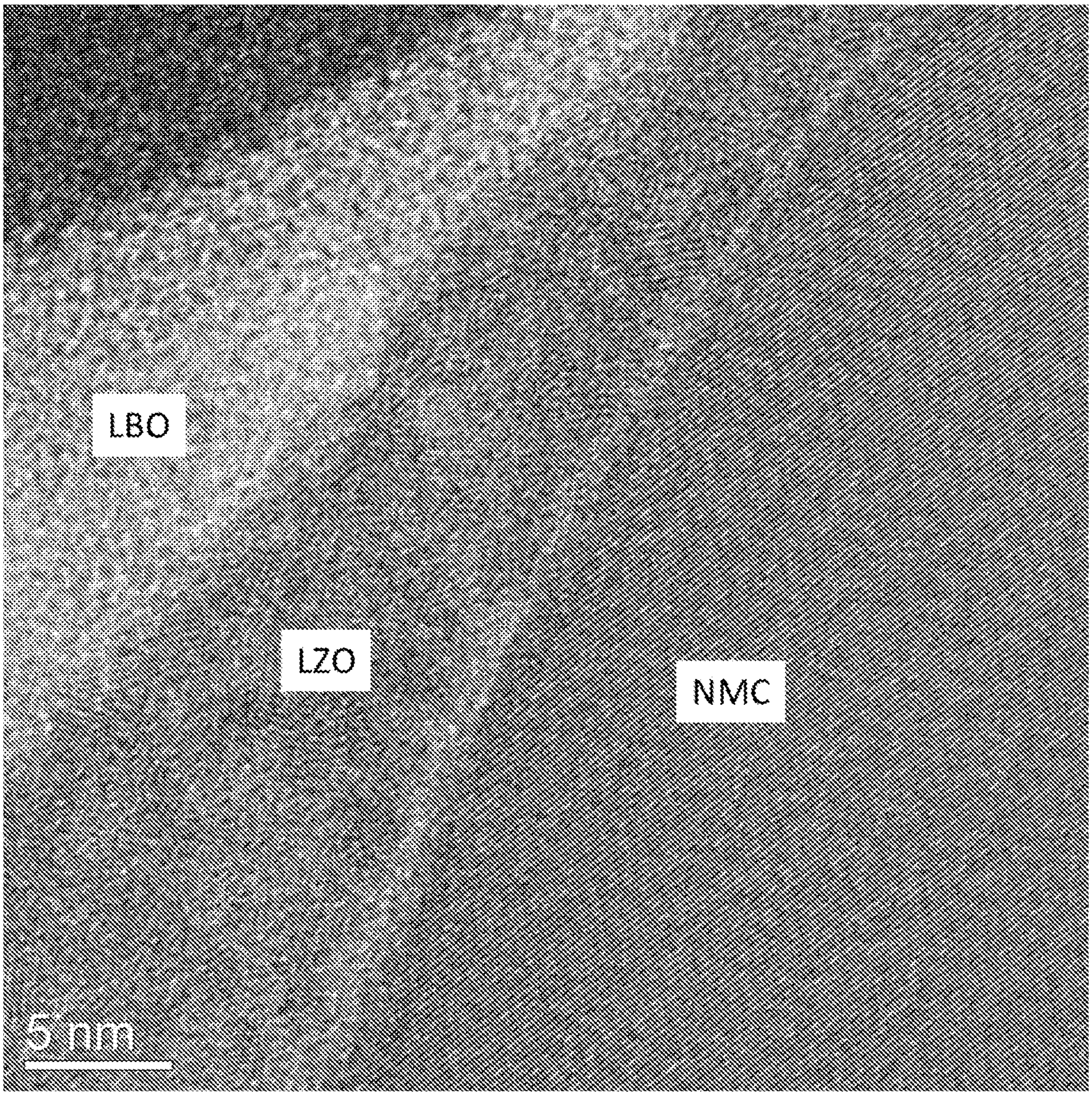

FIG. 5

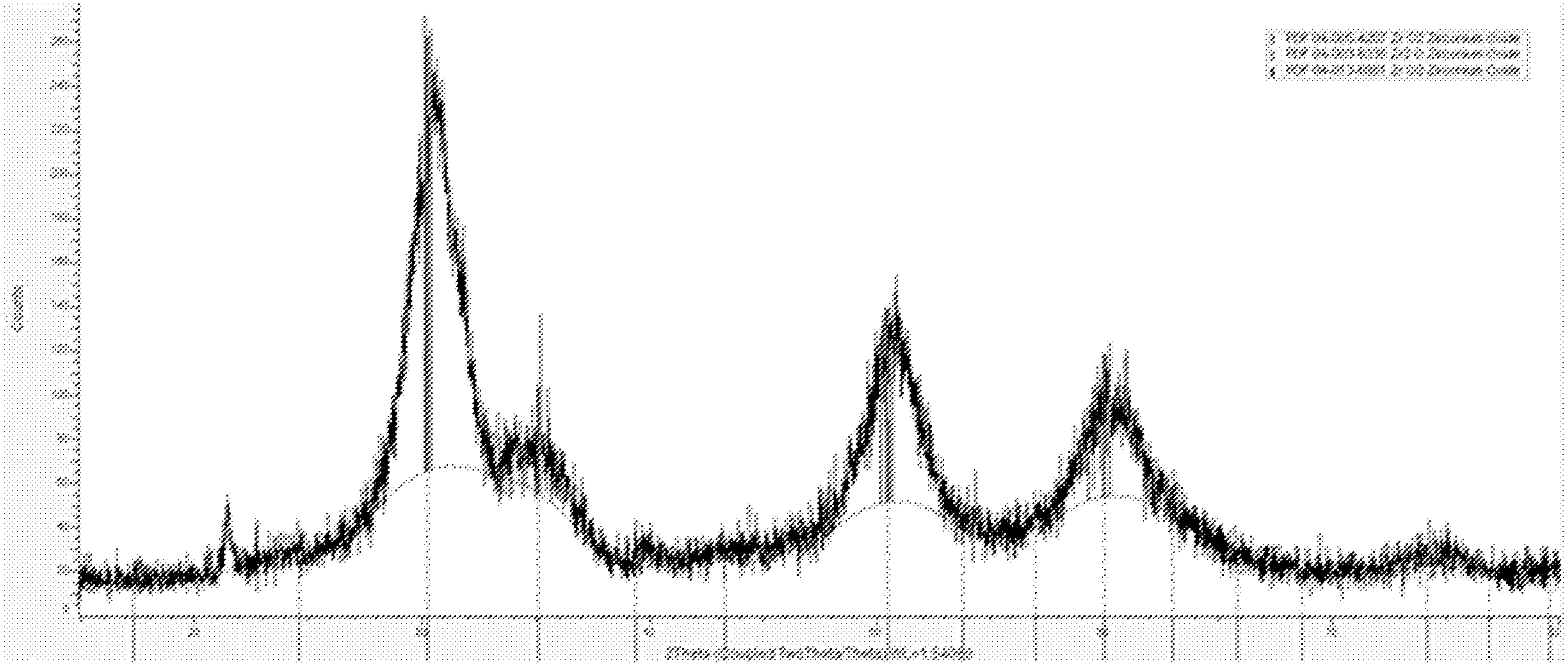

FIG. 6

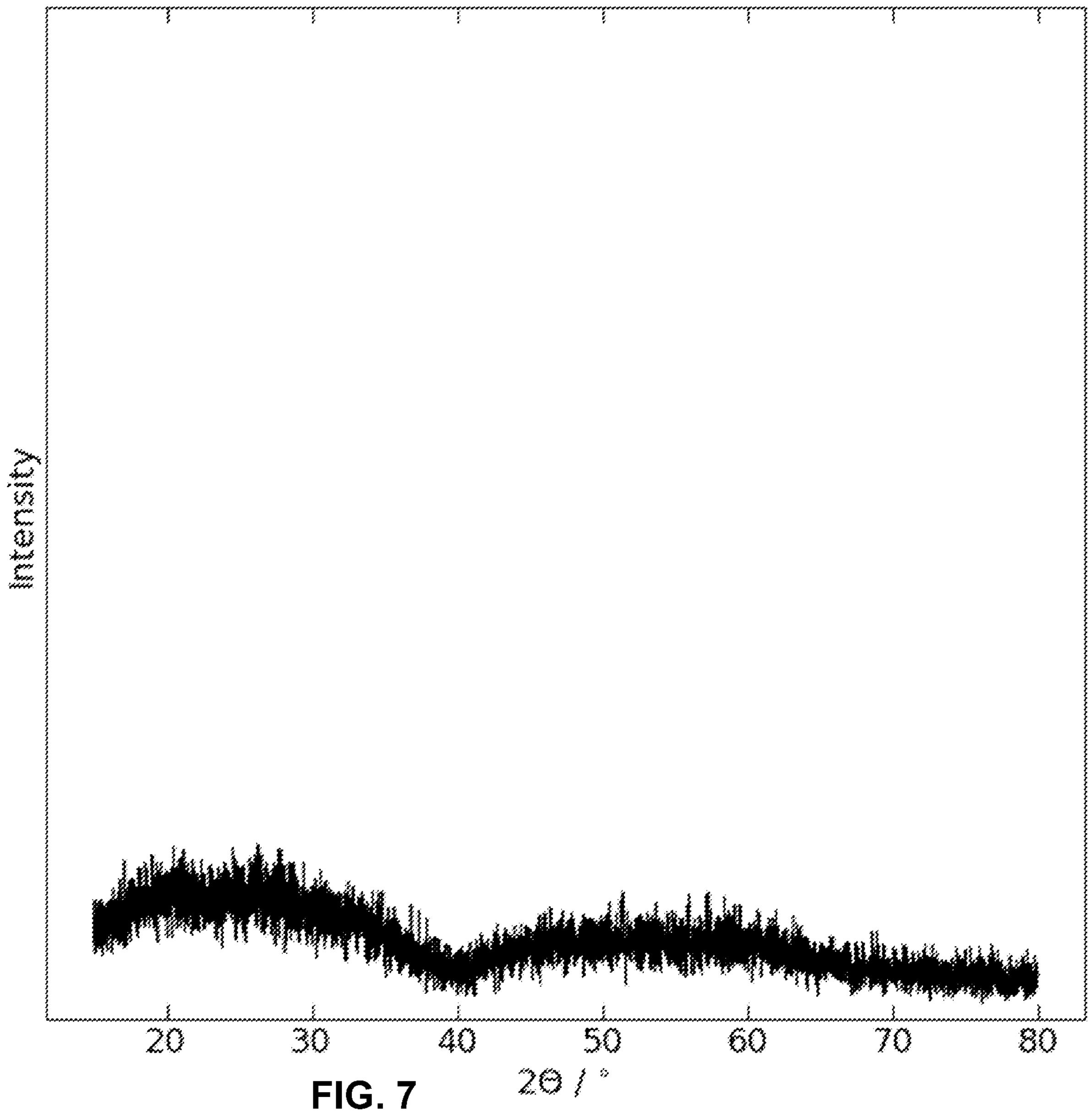

FIG. 7

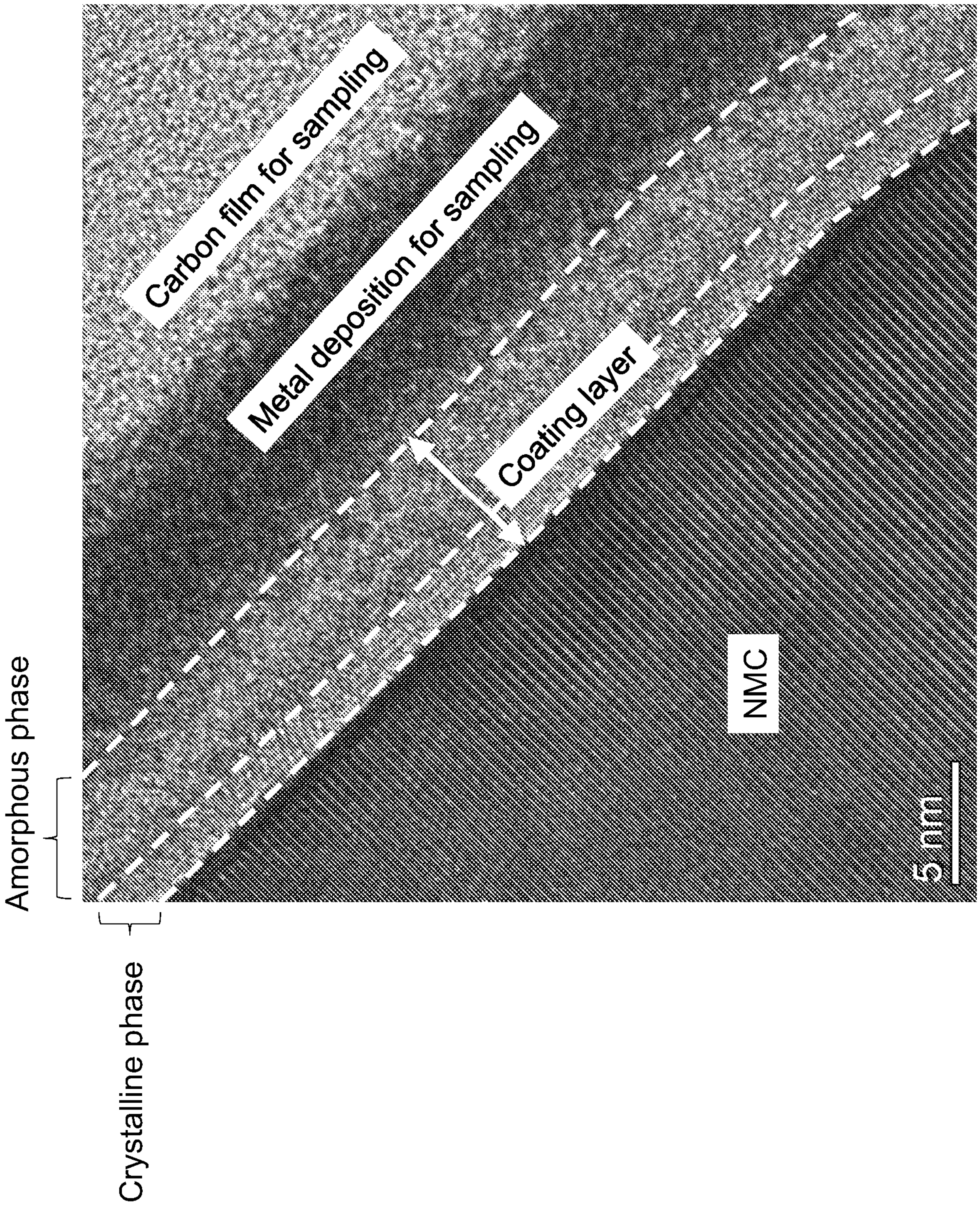
Carbon film for sampling
Metal deposition for sampling
Coating layer
NMC
5 nm
Amorphous phase
Crystalline phase

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2021/049528

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01M4/131
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ZHANG YA-QIAN ET AL: "Direct Visualization of the Interfacial Degradation of Cathode Coatings in Solid State Batteries: A Combined Experimental and Computational Study", ADVANCED ENERGY MATERIALS, vol. 10, no. 27, 5 July 2020 (2020-07-05), page 1903778, XP055861049, DE ISSN: 1614-6832, DOI: 10.1002/aenm.201903778 Retrieved from the Internet: URL:https://onlinelibrary.wiley.com/doi/full-xml/10.1002/aenm.201903778>	1-8, 16-18, 24-29,31
Y	abstract, p. 1, p. 3 with figure 2 ----- -/--	9-15

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 November 2021	01/12/2021

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European Patent Office, P.B. 5818 Patentlaan 2
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Authorized officer
Radeck, Stephanie

2

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2021/049528

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2016/276658 A1 (CHOI SU AN [KR] ET AL) 22 September 2016 (2016-09-22)	1,2, 19-21, 23-25, 27,30
Y	paragraph [0005] - paragraph [0101] -----	9-15
Y	US 10 141 567 B2 (L&F CO LTD [KR]) 27 November 2018 (2018-11-27) paragraph [0005] - paragraph [0101] -----	9,10
Y	CN 110 137 561 A (CHINA AUTOMOTIVE BATTERY RES INST CO LTD; UNIV WESTERN ONTARIO) 16 August 2019 (2019-08-16) paragraph [0048]; figure 2 -----	11-14
Y	JP 2016 085843 A (TOYOTA IND CORP; KONAN GAKUEN) 19 May 2016 (2016-05-19) paragraph [0043] -----	11-13,15

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2021/049528

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2016276658 A1	22-09-2016	KR 20150063956 A	10-06-2015
		US 2016276658 A1	22-09-2016
		WO 2015083900 A1	11-06-2015
US 10141567 B2	27-11-2018	KR 20150063955 A	10-06-2015
		US 2016276659 A1	22-09-2016
		WO 2015083901 A1	11-06-2015
CN 110137561 A	16-08-2019	NONE	
JP 2016085843 A	19-05-2016	NONE	